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Natural range of variation of subalpine forests in the bioregional assessment area

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INTRODUCTION

Physical setting and geographic distribution

Geographic Distribution

Subalpine forests and woodlands (hereafter, collectively referred to as "subalpine forests") are distributed throughout the Sierra Nevada immediately above the red fir (*Abies magnifica*) and upper montane forest zone and below the alpine vegetation belt (Figure 1; Rundel et al. 1988). The elevational distribution of this forest type generally extends from approximately 2450–3100 m in the northern Sierra Nevada to about 2900–3660 m in the southern part of the range (Fites-Kaufman et al. 2007). On the east side of the Sierra Nevada, the lower elevation limit of subalpine and upper montane forests typically extends an additional 50 to 450 m upwards in elevation in the northern and southern portions of the range, respectively; upper elevation limits may extend an additional 20 to 100 m in elevation (Potter 1998). In the Sierra Nevada bioregion, subalpine forest extends from the higher elevations of the Warner Mountains of the Modoc National Forest to the Tulare and Kern County border on the Kern Plateau of the Sequoia National Forest (Griffin and Critchfield 1972). Subalpine forests also occur in the White and Inyo Mountains and Glass Mountain of the Intermountain semi-desert province (Miles et al. 1997), typically at 2620–3540 m elevation (Rundel et al. 1988). On the western slope of the Sierra Nevada, subalpine forests form a relatively contiguous belt from Madera County to Nevada County with more isolated populations to the north and south of this region.

Several tree species in subalpine forests have restricted or unique geographic distribution patterns in the Sierra Nevada bioregion. Foxtail pine (*Pinus balfouriana*) is a California endemic with disjunct populations located in the Klamath Mountains and southern Sierra Nevada (Rundel et al. 1988); core southern populations are located in the upper South Fork of the Kern River drainage (Griffin and Critchfield 1972). Limber pine (*P. flexilis*) is primarily restricted to the east side of the southern and central Sierra Nevada, and does not occur further north than the Sweetwater Mountains in Mono County on the Toiyabe National Forest. This species also occurs in the White and Inyo Mountains and Glass Mountain of the Inyo National Forest (Miles and Goudey 1997). Great Basin bristlecone pine (*P. longaeva*; hereafter referred to as "bristlecone pine") is restricted to the higher elevations of the White, Inyo, and Panamint Mountains of the western Great Basin. Mountain hemlock (*Tsuga mertensiana*) is primarily restricted to the northern and central Sierra Nevada and is not found south of Silliman Lake in Sequoia National Park (Griffin and Critchfield 1972, Parsons 1972). Both western white pine (*P. monticola*) and lodgepole pine (*Pinus contorta* ssp. *murrayana*) occur throughout the upper elevations of the Sierra Nevada, although western white pine gradually declines in occurrence south of Kings River on the west slope and south of Twin Lakes on the east slope (Griffin and Critchfield 1972). Whitebark pine (*P. albicaulis*) is primarily located in the central and southern Sierra Nevada, especially north of the Kings River watershed and Kings–Kern Divide in Sequoia National Park (Vankat and Major 1978). Only small and isolated populations of whitebark pine exist in the northern portion of the assessment area, located primarily in the Lassen Volcanic National Park area and higher elevations of the Warner Mountains, due to the limited amount of high elevation habitat in the northern subregion. The southern Sierra Nevada represents the southern extent of the geographic distribution of whitebark pine, western white pine, foxtail pine, and mountain hemlock. Bristlecone pine populations in the White, Inyo, and Panamint Mountains represent the western extent of the geographic range of the species (Griffin and Critchfield 1972).

Subspecies Distributions and Genetic Structure

Subalpine conifer populations in the Sierra Nevada bioregion, especially the southern Sierra Nevada, are unique and distinct from other regions in western North America. Throughout its distribution, whitebark pine is clustered by genetic similarity into three main groups: Sierra Nevada, the greater Yellowstone region, and other areas including the northern Cascades, southern Oregon, and central and northern Idaho (Richardson et al. 2002). Of these three groups, Sierra Nevada populations have the highest degree of genetic divergence that may be considered contemporary refugia (i.e., area where climate and vegetation type have remained relatively unchanged while surrounding areas have changed markedly). Similarly, limber pine populations in California are genetically distinct from all other populations in western North America, and the southern Sierra Nevada likely represents a regional refugium for California populations (Mitton et al. 2000). Sierra Nevada populations of western white pine also show a relatively high degree of genetic differentiation compared to other more northerly populations throughout the species range (Kim et al. 2011). The Sierra Nevada subspecies of lodgepole pine (*P. contorta* ssp. *murrayana*) only occurs in the Sierra Nevada, Southern California mountains, Klamath Mountains, and high Cascade Range (Anderson 1996). The southern Sierra Nevada subspecies of foxtail pine (*P. balfouriana austrina*) is morphologically, genetically, and ecologically distinct from the northern California subspecies (*P. b. balfouriana*; Mastrogiuseppe and Mastrogiuseppe 1980, Maloney 2011), and molecular evidence suggests a divergence of these subspecies in the early to mid-Pleistocene (0.13–2.45 million years ago; Eckert et al. 2008). Population genetic differentiation within the southern subspecies of foxtail pine tends to be lower than the northern subspecies, presumably due to lower degrees of topographic isolation in the southern Sierra Nevada (Oline et al. 2000).

Overall, high-elevation pines in the assessment area exhibit moderate to high levels of genetic diversity, comparable to other pine species in western North America (Lee et al. 2002, Maloney et al. in review, Rogers et al. 1999) and relatively greater than other conifers with restricted ranges in California (Eckert et al. 2008). Westfall and Millar (2004) and Eckert et al. (2008) propose that this genetic diversity within populations may be a consequence of the complex relationship between cyclic climatic variation, biogeographical processes (e.g., dispersal into glacial refugia), and the non-equilibrium evolutionary response of high-elevation conifers, underscoring the dynamic distributional patterns within these forests.

Climatic Relationships

Subalpine forests are characterized by prolonged winter snowpack, a short growing season, and cool summer and cold winter temperatures (Table 1; Agee 1993, Fites-Kaufman 2006). Precipitation mainly occurs as winter snow and during the summer months is limited to locally intense convectional storms (Fites-Kaufmann et al. 2007). Recent climate trends indicate that the mean annual and monthly temperatures have increased in the higher elevations (>2200 m) of the Sierra Nevada, especially within the past 30 years (Das and Stephenson 2013, Diaz and Eischeld 2007, Edwards and Redmond 2011, Safford et al. 2012). Moreover, the annual number of days with below-freezing temperatures at higher elevations has declined, resulting in a 40–80% decrease in spring snowpack over the last 50 years in the northern and central Sierra Nevada (Moser et al. 2009). Snowpack in the southern Sierra Nevada has increased 30–100% over the same period, possibly owing to the relatively higher elevation terrain of the region. Precipitation has remained stable or steadily increased over

the past several decades in the higher elevations of the Sierra Nevada (Edwards and Redmond 2011, Safford et al. 2012).

Geology, Topography, and Soils

Subalpine forests occur on variable parent materials and soils, although most parent materials are granitic in the south, volcanic in the north, or either type in the central Sierra Nevada (Potter 1998, Sawyer et al. 2009). Topographic, soil, and microclimate associations of subalpine forests are highly variable, but in general most subalpine conifers (especially high elevation white pines) are restricted to less productive sites on drier soils (Table 2). Soils of subalpine forests are typically classified as Inceptisols (limited profile development) and Entisols (no sign of profile development; Laacke 1990, Potter 1998). Soils are typically frigid, shallow, acidic, xeric, and variable in texture and available water holding capacity. In general, subalpine soils tend to be shallow due to repeated glaciation during the Pleistocene (Fites-Kaufman et al. 2007). Available water holding capacity (AWC; top 100 cm of soil profile) in subalpine forest is typically between 70–80 mm (Lutz et al. 2010, NRCS 2013, Potter 1998). Topsoil and subsoil textures are usually sandy loams, sands, and loams, but include other texture classes (Potter 1998).

Landscape Patterns

Subalpine landscapes consist of a mosaic of subalpine forests and woodlands, rock outcrops, scrub vegetation, meadows and riparian ecosystems (Figures 2a, 2b; Fites-Kaufman et al. 2007). Subalpine forests typically comprise less than half of this landscape, especially at higher elevations. Granitic and other rock outcrops can constitute a substantial proportion of subalpine forest landscapes, creating large patches of open and treeless areas that support sparse vegetation cover. This is particularly apparent at higher elevations (>3000 m) and in the drier eastern Sierra Nevada, where harsher environmental conditions limit forest productivity and biomass. The underlying physical template and corresponding soil development and moisture patterns largely drive this variation within subalpine landscapes, resulting in a heterogeneous mixture of contiguous groves, open woodlands, individual tree clusters, shrub patches, wet and dry meadows, tree islands, and riparian corridors (Keane et al. 2012; Potter 1998). These conditions favor the coexistence of both shade-tolerant and shade-intolerant subalpine conifer species in high elevation landscapes (Table 2; Rundel et al. 1988).

Ecological setting

Indicator Species and Vegetation Classification

The primary indicator species that define subalpine forests of the Sierra Nevada bioregion include whitebark pine, foxtail pine, limber pine, bristlecone pine, western white pine, lodgepole pine, and mountain hemlock (Figures 2a, 2b; Fites-Kaufman et al. 2007). Common associates of subalpine forests include red fir, Sierra juniper (*Juniperus occidentalis*) and Jeffrey pine (*Pinus jeffreyi*) at lower elevations. Uncommon associates may include mid-elevation forest species such as white fir (*Abies concolor*), especially in the southern Cascades (Rundel et al. 1988). The California Wildlife Habitat Relationships (CWHR) system recognizes two vegetation types (subalpine conifer, lodgepole pine) that are considered subalpine forests in the assessment area (Mayer and Laudenslayer 1988). There are eight Calveg types that are included as subalpine forests, including bristlecone pine, foxtail pine,

limber pine, mountain hemlock, whitebark pine, western white pine, lodgepole pine, and subalpine conifers (USFS 2013). Sawyer et al. (2009) recognizes eight vegetation alliances and 52 associations of subalpine forests in the Sierra Nevada. Subalpine alliances include both subalpine forests (whitebark pine, lodgepole pine, western white pine, and mountain hemlock alliances) and woodlands (foxtail pine, limber pine, and bristlecone pine alliances).

Ecological Importance of Subalpine Forests

Subalpine forests provide a diverse array of ecosystem services, including watershed protection, soil formation, erosion control, carbon sequestration, and habitat for a diverse array of species in the Sierra Nevada (Keane et al. 2012). Subalpine tree species such as whitebark pine are also considered a keystone and foundation species in many high elevation ecosystems throughout the western United States (Tomback and Achuff 2010). Although subalpine forests support a less diverse fauna than lower elevation terrestrial ecosystems, a number of wildlife species depend on subalpine forests for foraging, nesting, or denning (Mayer and Laudenslayer 1988). Subalpine forests are particularly important for several sensitive and rare species such as American marten (*Martes caurina*), great gray owl (*Strix nebulosa*), Sierra Nevada red fox (*Vulpes vulpes necator*), wolverine (*Gulo gulo luteus*), white-tailed jackrabbit (*Lepus townsendii*), snowshoe hare (*Lepus americanus*), and heather vole (*Phenacomys intermedius*; Mayer and Laudenslayer 1988). Avian species that depend on subalpine forests include Clark's nutcracker (*Nucifraga columbiana*), mountain bluebird (*Sialia currucoides*), red crossbill (*Loxia curvirostra*), pine grosbeak (*Pinicola enucleator*), Cassin's finch (*Carpodacus cassinii*), Williamson's sapsucker (*Sphyrapicus thyroideus*), and black-backed woodpecker (*Picoides arcticus*; Mayer and Laudenslayer 1988). Clark's nutcracker, Douglas' squirrel (*Tamiasciurus douglasii*), lodgepole chipmunks (*Neotamias speciosus*), and other seed-caching wildlife species are important seed dispersers and predators of subalpine tree species in the assessment area (Table 2; Tomback 1982, Vander Wall 2008).

Holocene Forest Development

Refer to Red Fir NRV chapter and Table 3 for information.

Cultural, Socioeconomic, and Historical Setting

Cultural and Socioeconomic Significance of Subalpine Forests

Refer to Red Fir NRV chapter for information.

METHODS

Variables, Scales, and Information Availability

There were several variables that lacked sufficient historical information for their inclusion in this assessment (Table 4). However, for nearly all these variables contemporary references sites provide surrogate information that is complementary to the historic range of variation. For additional background pertaining to NRV information sources, refer to Red Fir NRV chapter.

Historic Reference Period

The historic reference period of Sierra Nevada subalpine forests includes much of the Holocene and extends into the present era (early 21st century). Exceptions include those relatively few, lower-elevation subalpine forests that were subjected to early logging activities during the late 19th and early 20th centuries, especially in the northern and central Sierra Nevada (Beesley 1996, McKelvey and Johnston 1992). Beginning in the early 1860s, the widespread and intensive impacts of sheep grazing and sheepherder burning practices were pervasive in the high elevation forests of the Sierra Nevada (McKelvey and Johnston 1992, Vankat 1970). Moreover, fire suppression activities begin in the mid-1920s, influencing fire regimes in many Sierra Nevada ecosystems, including subalpine forests. Consequently, information pertaining to fire regimes, understory vegetation, surface fuel loading, and historical tree recruitment in Sierra Nevada subalpine forests arguably requires a historic reference period that predates the 1860–1920 period. Nevertheless, a number of subalpine forests in the bioregion were relatively unperturbed by these historical impacts (e.g., arid subalpine woodlands), providing a number of likely contemporary reference sites for these forest ecosystems (although see Red Fir NRV chapter for pervasiveness of sheep grazing impacts). More importantly, recent climate warming at high elevations (see Climate Relationships section) indicate that the appropriate historic reference period in Sierra Nevada subalpine forests occurs prior to this relatively recent era of regional climate warming (i.e., prior to 1970). The historic reference period for subalpine forests is summarized in Table 9.

NRV DESCRIPTIONS AND COMPARISONS TO CURRENT CONDITIONS

Function

Fire

Fire Return Interval, Fire Rotation, and Fire Return Interval Departure

Historic Fire Return Interval (FRI) estimates for subalpine forests in the Sierra Nevada were highly variable (range: 19–187 years) and largely dependent on forest type (Table 5). In general, mean and median FRI values were longest in undefined "subalpine forest", moderately long in whitebark pine and mixed red fir–western white pine–mountain hemlock forests, and shortest in the lodgepole pine and western white pine forests. Mean FRI estimates for foxtail pine and bristlecone pine varied up to an order of magnitude (Table 5), possibly due to the relatively larger survey areas used by North et al. (2009); FRI estimates tend to increase with increased survey area (Agee 1993). Limited fire scar or contemporary fire history data from foxtail pine stands in the southern Sierra Nevada suggest FRI estimates between 130 and 260 years (Keifer 1991, Rourke 1988), which supports model estimates (~250 years) for these xeric subalpine forests (Stephenson et al. 2005). Based on a reconstruction of the annual area burned, Caprio and Graber (2000) noted that mean and maximum FRI estimates for subalpine forests in Sequoia and Kings Canyon National Parks tended to be greater on relatively mesic north-facing slopes (mean FRI = 374; max FRI = 1016 years) compared to xeric south-facing slopes (mean FRI = 187; max FRI = 508 years). However, Taylor (2000) found median FRI estimates were similar across all slope aspects in red fir–mountain hemlock forests of Lassen Volcanic National Park.

Fire rotation estimates for historic subalpine forests were variable across the Sierra Nevada. In the southern Cascades (pre-1905 period), fire rotation varied between 46 years for lodgepole pine forests and 147 years for red fir–mountain hemlock forests (Bekker and Taylor 2001). Taylor and Solem (2001) and Taylor (2000) estimated a presettlement (1735–1849) fire rotation of 76 years in lodgepole pine, red fir, and other upper montane forests in the southern Cascades. In Yosemite National Park, contemporary (1980–2000) fire rotation estimates based on lightning fires that were allowed to burn under prescribed conditions was 579 years in dry lodgepole pine forests (van Wagtendonk and Fites-Kaufman 2006). In foxtail pine stands of the southern Sierra Nevada, contemporary fire rotation estimates was 2100 years based on all fires and 7200 years for lightning fires only (Rourke 1988).

Few fires of notable size (>10 ha) have burned during the fire suppression time period in subalpine forests of the Sierra Nevada (Beaty and Taylor 2009, Bekker and Taylor 2001, Hallett and Anderson 2010), with the exception of contemporary reference sites with active fire regimes (e.g., Collins et al. 2007). This absence of fire has led to an increase in FRI and fire rotation in contemporary compared to presettlement subalpine forests (e.g., Bekker and Taylor 2001, Taylor and Solem 2001). Moreover, the absence of fire has also increased the backlog of subalpine forests that require fire for ecological benefits, as indicated by an increase in Fire Return Interval Departure (FRID) values in these forests (Caprio and Graber 2000, North et al. 2012). However, most Sierra Nevada subalpine forests have missed only one or two fire cycles at most (i.e., mostly low to moderate FRID), suggesting that the ecological effects of fire suppression in these forests are relatively minor or negligible compared to the fire-frequent mixed-conifer and yellow pine forests (Long et al. 2013, Miller and Safford 2012, van Wagtendonk et al. 2002).

Future Projections in Fire Frequency, Probability, and Area

Projections of future fire frequency, probability, and total burned area are expected to increase in the coming decades. Westerling et al. (2011) projected a more than 100% increase in annual area burned in many mid to high-elevation forests of the western Sierra Nevada by 2085 (Westerling et al. 2011). In Yosemite National Park, annual burned area is projected to increase 19% by 2020–2049 due to projected decreases in snowpack in mid- and high-elevation forests (Lutz et al. 2009b). Projections of future fire probability and frequency are expected to more than double by the end of the century (Figure 3; Mortiz et al. 2013). These projected increases were consistent across climate models that project hotter and drier (GFDL) and warmer and similar precipitation (PCM) climate conditions. Additionally, these results support earlier climate models that projected increased future fire occurrence in subalpine forests (Miller and Urban 1999). Increases in projected fire probability indicate that fire frequency will increase, leading to a decrease in return intervals and fire rotations for subalpine forests in the assessment area.

Fire Size

There are few historic estimates of fire size in Sierra Nevada subalpine forests. Mean fire size in the southern Cascades (1729–1918 period) was 405 ha (range: 295–460 ha) in lodgepole pine forest and 140 ha (range: 124–155) in red fir–mountain hemlock forest (Bekker and Taylor 2001). In Lassen National Park, mean fire size was 176 ha (median = 129 ha; range: 11–733 ha) in red fir–mountain hemlock forest (Taylor 2000). In the Lake Tahoe Basin, presettlement spatial patterns of fire-scarred trees in red fir–western white pine forests suggested that historic fires were small and patchy, but pulses of recruitment indicated that larger areas of moderate severity fire also occurred on the landscape (Scholl and Taylor 2006).

Based on contemporary reference sites, size of unsuppressed fires in subalpine forests vary widely but tend to be less than 4 ha in size. In upper montane and subalpine forests of the Emigrant Basin Wilderness Area between 1951 and 1973, nearly 80% of lightning-caused fires were less than 0.1 ha and none were larger than 4 ha (Greenlee 1973 in Potter 1998). In Sequoia and Kings Canyon National Parks between 1968 and 1973, 80% of unsuppressed fires were smaller than 0.1 ha and 87% were smaller than 4 ha (Potter 1998). In Yosemite National Park, 56% of unsuppressed fires in red fir and lodgepole pine forests between 1972 and 1993 were less than 0.1 ha and 82% were smaller than 4 ha (Figure 4; van Wagtendonk 1993). In contrast to average fire size, the highest proportion of area burned (>70%) in red fir and lodgepole pine forests of Yosemite National Park tends to be from fires between 4 and 400 ha in size (van Wagtendonk 1993); an additional 28% of burned area is attributed to fires between approximately 400 and 2000 ha in size (Figure 5).

There is a recent trend toward increasing fire size and total burned area in moister and higher elevation forests of the Sierra Nevada. Between 1984 and 2004, total annual burned area has increased in red fir, white fir, and subalpine forests of the Sierra Nevada (Miller and Safford 2008, Miller et al. 2009). Mean and maximum fire size have also increased during this time period in higher elevation forests of the Sierra Nevada.

Fire Type

Sierra Nevada subalpine forests are currently split into two general fire types, based on contemporary reference site information. In the first type, both high-elevation white pine forests (i.e., whitebark

pine, foxtail pine, limber pine, and bristlecone pine) and open western white pine–Jeffrey pine forests typically experience slow-moving surface fires due to the presence of sparse surface and canopy fuels, natural terrain breaks, and relatively drier conditions that support lower tree densities and biomass (van Wagtendonk and Fites-Kaufman 2006, Keane et al. 2012). Occasional local torching of individual tree or tree clumps does occur in these forests, particularly under extreme dry and windy conditions. The second general fire type is represented by subalpine forests dominated by lodgepole pine or mountain hemlock. These relatively mesic forests are characterized by a mixture of semi-frequent surface fires with occasional crown fires, resulting in "multiple" fire types that are dependent on localized fire weather and fuel loading conditions (Agee 1993, van Wagtendonk and Fites-Kaufman 2006). The relatively higher frequency of crown fires in these forests are supported by the presence of heavy and compact surface fuels, higher tree densities, and greater rates of litter and woody fuel deposition (van Wagtendonk and Fites-Kaufman 2006, van Wagtendonk and Moore 2010). Sustained crown fires in these forests often only occur under extreme dry and windy conditions (Keifer 1991, van Wagtendonk and Fites-Kaufman 2006). In high-elevation lodgepole pine forests of Yosemite National Park, Muir (1894) remarked:

> *"During the calm season and Indian summer the fire creeps quietly along the ground, feeding on the needles and cones; arriving at the foot of a tree, the resin bark is ignited and the heated air ascends in a swift current, increasing in velocity and dragging the flames upward. Then the leaves catch, forming an immense column of fire, beautifully spired on the edges and tinted a rose-purpose hue. It rushes aloft thirty or forty feet above the top of the tree, forming a grand spectacle, especially at night. It lasts, however, only a few seconds, vanishing with magical rapidity, to be succeeded by other along the fire-line at irregular intervals, tree after tree, upflashing and darting, leaving the trunks and branches scarcely scarred." [Underlining added]*

These observations support current studies in contemporary reference sites that these forests were characterized by relatively frequent surface fires interspersed with occasional wind-driven crown fires (e.g., Caprio 2006, Keifer 1991). Interestingly, fire type roughly parallels fire tolerance of subalpine tree species, with more tolerant species usually associated with surface fire types (Table 2).

Subalpine forests are generally characterized by a climate-limited fire regime at landscape and regional scales, although fuels can limit fire spread at localized scales in patchy, sparsely-vegetated subalpine stands (Brown and Smith 2000, van Wagtendonk and Fites-Kaufman 2006). Climate-limited fire regimes typically have sufficient fuel to carry fire, but fire occurrence depends primarily on whether climate or weather is suitable for ignition and fire spread (Agee 1993). In Late Holocene, fire activity in subalpine forests of the Sierra Nevada was driven by changes in climate, including the dynamics of the El Niño–Southern Oscillation. (Hallett and Anderson 2010).

Together, these studies suggest that historic and current fire regimes in subalpine forests are both climate-limited and dominated by either surface fires or a combination of surface fires with occasional crown fires. Consequently, fire regime types of subalpine forests are likely within the historic range of variation.

Fire Seasonality

Most fires in subalpine forests historically occurred during the late summer or fall (van Wagtendonk and Fites-Kaufman 2006). In lodgepole pine and red fir–western hemlock forests of the southern Cascades, the position of fires on presettlement annual growth rings indicated that 99–100% of historic fires burned during the late summer and fall (Bekker and Taylor 2001, Taylor 2000). In the Lake Tahoe Basin, 92% of historic fires in red fir–western white pine forests burned during the late summer to fall, and 7% burned in the early to mid-summer (Taylor 2004). Whitebark pine forests burned throughout the growing season, but most fires (especially large fires) occurred late in the season (Agee 1993). In high elevation forests of Yosemite National Park, most wildfires and wildland use fires between 1974 and 2005 burned during the months of July, August, and September (van Wagtendonk and Lutz 2007). Together, these studies indicate that fire season has not changed substantially between historic and current periods.

Fire Severity

Fire regimes of subalpine forests in contemporary reference sites have been classified as either low-severity or mixed-severity (generally characterized by "multiple" fire severity classes). High-elevation white pine forests typically experience low severity fire (often <25% tree mortality), and mesic lodgepole pine or mountain hemlock forests are generally characterized as mixed-severity (Table 6; Agee 1993, Brown and Smith 2000, van Wagtendonk and Fites-Kaufman 2006, Keane et al. 2012). For instance, Thode et al. (2011) concluded that the whitebark pine–mountain hemlock had a low-severity fire regime distribution and lodgepole pine had a multiple fire regime distribution based on fires that burned between 1984 and 2003 in Yosemite National Park. The proportion of area burned at high-severity (>75–95% tree mortality with high to complete mortality of vegetation) averaged 27% and 7% across studies in lodgepole pine and other subalpine forests, respectively (Table 6). Re-burned lodgepole pine stands in Yosemite National Park tended to burn at higher severity compared to stands not recently burned (van Wagtendonk et al. 2012). Unmanaged wildfires also tended to burn at greater severity relative to prescribed fires and "wildland fire use" fires (i.e., wildfires managed for resource objectives) across upper and lower montane forests in Yosemite National Park during 1974–2005 (van Wagtendonk and Lutz 2007).

Miller et al. (2009) found that fire severity in Sierra Nevada subalpine forests was negatively correlated with spring precipitation, but temporal trends (1984–2006) in fire severity was not apparent due to insufficient data for the subalpine zone. Consequently, current fire severity may be within the historic range of variation, but additional analysis will be required to understand future trajectories.

Future Projections in Fire Severity and Intensity

Projections of future climate suggest that fire severity or intensity may increase in many parts of the Sierra Nevada during the mid-21st century, especially in subalpine forests (Lenihan et al. 2003, 2008). In Yosemite National Park, the total area burned at high severity in mid- and high-elevation forests is projected to increase 22% between the current (1984–2005) and mid-21st century (2020–2049) periods, due to declines in snowpack (April 1 snow water equivalent; Lutz et al. 2009b).

High Severity Patch Size

Presettlement information related to high severity patch size is limited to sparse historic accounts. Muir (1894) observed that high-elevation stands of lodgepole pine experienced stand-replacing fire events that were frequently small and patchy but in some cases "miles in extent...leaving a forest of bleached spires...encumbering the ground until, dry and seasoned, they are consumed by another fire." In addition, he emphasized "during strong winds whole forests are destroyed, the flames surging and racing onward above the bending woods, like the grass-fire of a prairie." In combination with related observations (see quote under Fire Type section), Muir's various accounts suggest that some presettlement lodgepole pine forests in Yosemite endured rare wind-driven fire events that resulted in large stand-replacing patches.

Stand-replacing high severity patches in contemporary reference subalpine forests were typically defined as areas exceeding 95% tree mortality, with high to complete mortality of vegetation (Miller and Safford 2008; Figure 6). In montane forests of the Illilouette Creek Basin of Yosemite National Park (including lodgepole pine forests), the mean patch size of stand-replacing, high-severity burned patches following the Hoover Fire (2001) and Meadow Fire (2004) was 9.1 ha (median = 2.2 ha; Collins and Stephens 2010). The median patch size of stand-replacing patches in lodgepole pine forests was approximately 1.5 ha, although median patch size increased to about 20 ha in mixed stands of red fir–white fir–lodgepole pine. Most (>60%) of the stand-replacing patches in montane forests in the Illilouette Creek Basin were ≤4 ha in size, but a few large patches accounted for ~50% of the total stand-replacing patch area.

Collectively, historic accounts and contemporary reference site information suggests that presettlement stand-replacing patches in subalpine lodgepole pine forests were primarily small in size but also included occasional large-sized patches as a consequence of extreme fire weather conditions (e.g., high winds, low fuel moistures). Conditions in other subalpine forest types are uncertain. Current temporal trends in high severity patch size are not available due to insufficient information in current non-reference subalpine forests (Miller and Safford 2008, Miller et al. 2009).

Insects

Native insect outbreaks have occurred within the Sierra Nevada almost every decade of the 20th century (Ferrell 1996, FRAP 2010). Mountain pine beetle (*Dendroctonus ponderosae*) was responsible for a significant portion of this historic tree mortality in subalpine forests, often acting in concert with drought, pathogens, and other stressors (Ferrell 1996). Subalpine host species of mountain pine beetle includes lodgepole pine, whitebark pine, western white pine, limber pine, foxtail pine, and bristlecone pine (Furniss and Carolyn 2002). Other native insects and pathogens in subalpine forests are covered in the Red Fir NRV and Yellow Pine and Mixed Conifer NRV chapters.

Both historic records and long-term paleoecological records indicate that significant mountain pine beetle outbreaks in western North America occurred at irregular intervals initiated by regional drought (Gibson et al. 2008) or rapid climate transitions (Brunelle et al. 2008). In contrast, Ferrell (1996) reviewed forest insect damage reports for the Sierra Nevada from 1917 to 1993 and found that mountain pine beetle outbreaks in subalpine forests were infrequent and usually limited to small clumps of trees; although larger outbreaks in dense stands was not uncommon (California Forest Pest Council 1951–1993). It is not clear, however, whether historic insect damage surveys for the Sierra

Nevada were effective at detecting mountain pine beetle outbreaks within high-elevation subalpine forests, due to their relatively low economic importance and inaccessibility (Gibson et al. 2008). Consequently, historic information is inconclusive with respect to the frequency and extent of mountain pine beetle outbreaks in subalpine forests of the assessment area.

Recent modeling studies of mountain pine beetle activity throughout the western United States (including the assessment area) have provided insights into the natural range of variation in bark beetle outbreaks. Hicke et al. (2006) modeled historical (1895–1960), current (1961–2005), and future (2006–2100) mountain pine beetle outbreaks in forests of the western United States using climate factors closely associated with the synchronous emergence of adults from host trees at an appropriate time of year (termed "adaptive seasonality"). Their results indicate that the adaptive seasonality of mountain pine beetle was similar between historic and current periods for many parts of the western U.S., including the higher elevations of the Sierra Nevada. However, future projections in adaptive seasonality at high elevations (>3000 m) demonstrated that the total area susceptible to bark beetle attack would initially increase between 2005 and 2050, then steadily decline but remain above current levels between 2060 and 2100 (Figure 7; Hicke et al. 2006). Bentz et al. (2010) found similar results comparing current and projected future adaptive seasonality with a similar population model. These results suggest that future projections in mountain pine beetle outbreaks in subalpine forests of the Sierra Nevada will be outside the historic range of variation.

Several recent studies and reports lend support to model projections in mountain pine beetle activity within the assessment area. Since 2006, mountain pine beetle activity in subalpine forests dominated by western white pine and lodgepole pine has increased substantially above background levels, especially on the Modoc National Forest (California Forest Pest Council 2011). Whitebark pine and limber pine have recently experienced significant increases in mortality from mountain pine beetle, drought, and other stressors in the eastern Sierra Nevada on the Inyo (both species) and Modoc (whitebark pine only) National Forests (Millar et al. 2007, 2012, California Forest Pest Council 2011). Such outbreaks have led to significant changes in the structure, regeneration, and dominance of whitebark pine stands (Meyer et al. 2013). In many of these cases, increased mountain pine beetle activity has been clearly linked to increases in temperature and climatic water deficit, decreases in precipitation, and greater stand densities or tree diameters (Anderson et al. in review, Meyer et al. 2013, Millar et al. 2007, Millar et al. 2012), further implicating that future outbreaks in high-elevation subalpine stands are likely in the near future.

Collectively, these studies and reports indicate that mountain pine beetle outbreaks are currently within the historic range of variation for the assessment area, at least prior to the recent 2006–2012 outbreak events in high-elevation white pine stands of the Inyo and Modoc National Forests. However, near future (2006–2050) projections for high-elevation white pine forests in the assessment area suggest increased frequency and extent of outbreaks may greatly exceed the historic range of variation by the early- to mid-21st century. This projected increase in mountain pine beetle activity will have substantial cascading impacts on subalpine forest ecosystems of the assessment area similar to those observed recently in the central and northern Rocky Mountains (Edlburg et al. 2012).

Wind and Volcanism

Refer to Red Fir NRV chapter to information on wind and volcanism.

Climatic Water Deficit

Water balance relationships are important for evaluating climate controls on species distributions across spatial scales, including subalpine forests (Stephenson 1998). In Yosemite National Park, subalpine tree species occupied areas with the lowest evapotranspiration and climatic water deficit (Deficit) values relative to other montane tree species (Lutz et al. 2010). Lutz et al. (2010) also found that values of AET/PET (a measure of the relative sensitivity of species ranges to increases in climatic water deficit) for subalpine tree species in Yosemite were either well within the North American water balance envelope for each species (e.g., whitebark pine, lodgepole pine) or were clustered near the extreme arid end for its entire geographic range (e.g., mountain hemlock, western white pine), indicating high sensitivity of these species to changes in Deficit in Yosemite. In the Sierra Nevada annual rates of AET for subalpine conifers generally tended to increase with latitude (with corresponding decrease in Deficit), from approximately 225 mm (Deficit ≈ 110 mm) in Sequoia National Park (Stephenson 1998) to 248 mm (Deficit ≈ 63 mm) in Yosemite National Park (Lutz et al. 2010). This trend indicates greater moisture deficit in subalpine forest stands towards the southern portion of its range in the Sierra Nevada. In the southern Sierra Nevada, foxtail pine basal area was positively correlated with AET and negatively correlated with water vapor deficit during the summer in Sequoia National Park (Rourke 1988).

Modeled climatic water deficit (Deficit) averages for subalpine forests in Yosemite National Park were generally similar between the Little Ice Age (~1700 A.D.) and the present (1971–2000; Figure 8; Lutz et al. 2010). This suggests that Deficit is generally within the historic range of variation for subalpine tree species in the central Sierra Nevada. However, Deficit was projected to be 24–30% greater in the near future (2020–2049) compared to the present (1971–2000; Lutz et al. 2010), indicating an increasing trend of moisture stress in subalpine tree species such as mountain hemlock and western white pine.

Forest Dynamics at Treeline or Ecotonal Boundaries

Subalpine forests at or near treeline or ecotonal boundaries (e.g., lower elevation limit) are highly sensitive to changes in climate in the Sierra Nevada, although these patterns and their mechanisms are complex and often species specific (Table 7; Fites-Kaufman et al. 2006, Körner 1998, LaMarche 1973). Overall, these climate-dependent patterns indicate that treeline populations are generally within the broad historic range of variation, especially when comparing 20th century records with a historic reference period that spans both the Little Ice Age and Medieval Warm Period (Tables 3, 7). However, there is a general trend of increased growth, density, recruitment, and treeline elevation within subalpine tree populations located at or near treeline within the past 40 to 50 years (Table 7). For example, bristlecone pine tree-ring growth near treeline in the White Mountains (which was positively correlated with temperature) was greater during 1960–2010 than any other period during the last 3700 years (Salzer et al. 2009). In contrast, lower elevation stands of bristlecone pine had decreased growth associated with increased temperatures and decreased precipitation, indicating greater moisture limitations within lower-elevation stands. Foxtail pine populations may be an exception to these general trends for subalpine forests, with recent declines in recruitment and regeneration in foxtail pine treeline populations of the southern Sierra Nevada, possibly due to increased climatic water deficit resulting from higher temperatures and lower precipitation (e.g., Lloyd 1997, Lloyd and Graumlich 1997).

Structure

Tree Densities and Size Class Distribution

Tree densities and tree size class distribution are highly variable among subalpine forests due to the complex topography and variable species composition of subalpine landscapes (Rundel et al. 1988). For instance, size class distributions of high-elevation white pine stands differ considerably across tree species (Maloney et al. 2008, Maloney 2011), although current subalpine forests as a whole have a relatively even distribution excluding the regeneration class (Figure 9). However, several general patterns have emerged from recent studies examining changes in subalpine forest stand structure over the past century based on the comparison of historical inventories (e.g., Wieslander) with modern surveys (e.g., USFS Forest Inventory and Analysis) or historic stand reconstructions. In the central Sierra Nevada, tree density in subalpine forests increased by a net value of 30%, including a 44–91% increase in small tree (<30.4 cm dbh) density for whitebark pine, lodgepole pine, mountain hemlock, and red fir between 1934 and 2007 (Dolanc et al. 2012). In contrast to small tree density, however, large tree (≥61 cm) density declined in high-elevation species such as western white pine, lodgepole pine, and red fir (Dolanc et al. 2012, Dolanc in review). In addition, there was a net increase in tree densities in subalpine forests above 3000 m elevation, driven by increases in the smaller size class (Figure 10); similar patterns were also observed in subalpine stands between 2500 and 3000 m elevation. Lutz et al. (2009) estimated a 49% reduction in the density of large diameter (≥61 cm) lodgepole pine over roughly the same period in Yosemite National Park. Several other subalpine species showed large tree declining trends in Yosemite, but these were not significant. In secondary-growth lodgepole pine forests of the Lake Tahoe Basin, total tree density increased but average tree diameter decreased between pre-settlement and current periods based on stand reconstructions by Taylor (2004) and Taylor et al. (in press) (Figure 11), resulting in a significant shift in the size class distribution to smaller diameter trees (Figure 12). In Sequoia National Park, Vankat and Major (1978) compared historic and modern photos in subalpine forests, including foxtail pine and lodgepole pine stands, and found an apparent increase in tree density and cover between 1912 and 1978. Gruell (2001) also observed increased tree densities and cover while comparing historic (1867–1900) and contemporary (1990s) photos taken in subalpine forests throughout the Sierra Nevada.

William Brewer (1864) observed large-diameter trees and low tree densities in subalpine forests of modern-day Sequoia and Kings Canyon National Parks:

> *"Our route lay along the divide between the head branches of the Kings and Kaweah rivers, over steep ridges, some of them nearly ten thousand feet high, and then along ridges covered with forests of subalpine pines and firs... All grow to a rather large size, say four to five feet in diameter, but are not high. All are beautiful, the fir especially so, but there is difference enough in the color of the foliage and habit of the trees to give picturesque effect to these forests, which are not dense." [Underlining added]*

This historic account supports historic stand inventories documenting the low density of subalpine forest stands that were dominated by large-diameter (120–150 cm) trees.

Based on the historic–current stand inventory comparisons, stand reconstructions, and historic observations, it is likely that subalpine forests have increased in tree density and experienced a shift in their size class distribution to smaller size classes over the past 70–140 years. These changes are coinci-

dent with: (1) 19th century logging impacts in secondary growth stands (e.g., Taylor 2004), and (2) increases in daily minimum temperatures and precipitation over the past several decades that may favor increased regeneration, recruitment, and large-tree mortality rates in subalpine tree species (Dolanc et al. 2012, Dolanc in review).

Basal Area

Although there is limited information on historic basal area in subalpine forests of the Sierra Nevada, evidence suggests that basal area has not changed between historic and current periods. Taylor (2004) and Taylor et al. (in press) found that basal area was not different between pre-settlement and current lodgepole pine stands in the Lake Tahoe Basin (Figure 11).

Tree Spatial Patterns and Structural Diversity

Both historic and current tree spatial patterns in subalpine stands show distinct spatial patterns among subalpine tree species, partially contingent on seed dispersal mechanism (Table 2). Harris (1939) observed "scattered" foxtail pine stands in Sequoia National Park where "the spacing between the mature old foxtails is uniform," a pattern that reflects the random to uniform tree spacing patterns in current foxtail pine stands (Figure 2b; Keifer 1991). Both Muir (1894) and Leiberg (1902) remarked that whitebark pine had a "scattered" distribution in the Sierra Nevada that is similar to current clumped spatial patterns in the range (Keane et al. 2012, Meyer et al. 2013, Tomback 1982). Muir (1894) also observed that western white pine trees "grow in clusters of from three to six or seven." Historic photos by Wieslander et al. (1933) show generally similar clumped spatial patterns for whitebark pine, limber pine, and western white pine in historic subalpine stands.

In contrast to unlogged subalpine stands, high-elevation forests logged during the late 19th century are dissimilar to presettlement stands with respect to tree spatial patterns and structural diversity. Taylor (2004) analyzed tree spatial patterns in pre-settlement and current secondary-growth lodgepole pine stands in the Lake Tahoe Basin. Presettlement lodgepole pine forests were characterized by heterogeneity in tree spatial patterns; large to intermediate diameter trees (>40 cm) were clumped at all spatial scales and small diameter (10-40 cm) trees were randomly distributed (Taylor 2004). In comparison, current lodgepole pine forests contained small diameter trees that were clumped at all spatial scales, but large trees were randomly distributed. These results infer that the underlying structural patterns of pre-settlement and current secondary-growth lodgepole pine stands are different, despite relatively high structural heterogeneity in both periods. Structural diversity, defined as the dispersion and evenness of diameter size classes, was greater in pre-settlement than current secondary-growth lodgepole pine stands of the Lake Tahoe Basin (Figure 12), suggestive of a frequent, low-severity fire regime (Taylor 2004).

Canopy Structure

In the Lake Tahoe Basin, canopy height and canopy base height were similar between presettlement and contemporary lodgepole pine stands (Taylor et al. in press). However, canopy base height was greater in presettlement stands (mean: 7.3 m; range: 5.5–9.8 m) than contemporary stands (mean: 0.8 m; range: 0.6–0.9 m; Taylor et al. in press).

Understory Plant Cover

Historic information pertaining to understory vegetation and ground cover is primarily limited to historic accounts that predate the period of extensive sheep grazing in the high elevation forests of the Sierra Nevada. In his extensive travels of montane forests in the Sierra Nevada, Brewer (1864) remarked "The ground under the [subalpine] tree is generally nearly bare. There is but little grass or undergrowth of either herbs or bushes." In describing the subalpine landscapes, including "upper pine forests" and "glacier meadow gardens" in Yosemite National Park, Muir (1894) remarked "In some places the sod is so crowded with showy flowers that the grasses are scarce noticed, in others they are rather sparingly scattered." Historic surveys and photos by Harris (1939) indicated that outside riparian areas and mesic microsites, understory shrub cover (especially *Ribes*) in pure and mixed foxtail pine stands of Sequoia National Park was "intermittent" to "practically devoid of vegetation." Wieslander et al. (1933) historic forest inventories indicated low average coverage of understory vegetation in foxtail pine stands (1.3 ± 2.4%) but moderate coverage in whitebark pine stands (24 ± 31%) of the Sierra Nevada. These accounts suggest presettlement understory plant cover was spatially variable and relatively sparse in many subalpine stands, especially outside of subalpine meadows, riparian areas, and mesic microhabitats. Current understory patterns largely mirror these trends (Potter 1998, Rundel et al. 1988, Vankat and Major 1978), and are driven to a large extent by variability in the underlying substrate and soil moisture (see Landscape Patterns section of Introduction). For example, understory cover averages 13.4 ± 14.5 (SD) for herbaceous plants and 8.2 ± 12.8% for shrubs, based on an analysis of a total of 301 Forest Inventory and Analysis plots in subalpine forest plots of the assessment area. This general consistency between presettlement and current conditions implies that understory cover in contemporary subalpine forests is within the historic range of variation.

Physiognomic Patterns – Seral Class Proportions

LANDFIRE biophysical setting (BpS) modeling estimated that historic reference conditions in subalpine forests of the assessment area were dominated by mid- and late-seral classes. As an exception, the southern Sierra subalpine forest, or Mediterranean California subalpine woodland BpS model (dominated by whitebark pine, mountain hemlock, and red fir but may include foxtail pine, western white pine, and lodgepole pine), was defined only by mid- and early-seral classes (Figure 13). In general, subalpine forests had a greater proportion of mid- and late-seral classes with open canopies (<50% cover) than other montane forests in the assessment area, with the exception of wet lodgepole pine forests which were dominated by the late-seral closed-canopy seral class (Caprio 2005a, 2005b, Richardson and Howell 2005, Stephenson et al. 2005, van Wagtendonk et al. 2005).

LANDFIRE BpS modeling of the Stanislaus National Forest based on analyses at the subwatershed scale (7th field HUCs; ~800 to 2800 ha) indicated that current subalpine forests (i.e., southern Sierra subalpine forest and mesic subalpine woodland BpS models) contained a marginally greater proportion of the open-canopy mid-seral class (12% increase) and a lower proportion of closed-canopy mid-seral and early seral classes (7 and 4% decrease, respectively) than historic conditions (Figure 14; Safford and Schmidt 2006). In comparison, Sierra Nevada lodgepole pine–dry subalpine forest contained a greater proportion of the early-seral class (26% increase) and lower proportion of late-seral class (20% decrease) than historic conditions (Safford and Schmidt 2006). Assuming the Stanislaus National Forest is generally representative of the larger assessment area, these results suggest that there may be a current deficit of the late-seral class and surplus of early-seral classes in lodgepole

pine–dry subalpine forest, and minor surplus of the open-canopy mid-seral class in subalpine forests of the Sierra Nevada. However, analyses from additional national forests in the Sierra Nevada will be required to more thoroughly evaluate seral class trends within the assessment area.

Composition

Subalpine Tree Species Composition

Historic stand inventory and stand reconstruction studies indicate that tree species composition in subalpine forests is similar between historic and contemporary subalpine forests. In the central Sierra Nevada, modern stand composition was indistinguishable from historic composition based on stand inventory comparisons over a 70-year period (Dolanc et al. 2012). In the Lake Tahoe Basin, lodgepole pine forests at the lower elevational limit of subalpine forests did not change significantly in tree species composition between presettlement and current periods (Figure 12; Taylor 2004, Taylor et al. in press). Dolanc (in review) also found that changes in the relative frequency of high-elevation tree species in the northern and central Sierra Nevada was relatively minor, supporting the conclusion that species composition has remained relatively unchanged over the past 70 to 140 years.

PROJECTED FUTURE CONDITIONS AND TRENDS

Background

Refer to Red Fir NRV section.

Model Projections

Projected changes in the distribution of subalpine forests are summarized on Table 8. All studies used the A2 emissions scenario (high emissions), with the exception that Gonzalez (2012) used an ensemble of the B1 (lower emissions), A1B (moderate emissions), and A2 emissions scenarios with two GCMs (PCM, GFDL). Southern Sierra Partnership (2010) used only the A2 emissions scenario but included an ensemble of 11 GCMs. Ecological response models included species distribution models (BioMove, ANUCLIM, Maxent, Bioclim) in four studies but also included the MC1 vegetation dynamic model for biome projections in Lenihan (2003, 2008). Statistical procedures used to project changes in bristlecone pine distribution incorporated geology and topography but did not include information regarding the types of GCMs, emission scenarios, or species distribution models used (Van de Van et al. 2007).

Models projected a substantial 48–100% reduction in the geographic range size of all subalpine forests in the assessment area (Table 8). Reductions in the range size of specific subalpine species included 78–92% reduction in foxtail pine, 75–100% reduction in bristlecone pine, and 82–100% range reduction in whitebark pine across a range of geographic scales (subregional to entire species' geographic range). Projected loss of lodgepole pine (by 2040–2065) in the southern Sierra Nevada was more than twice that for the entire state of California (Southern Sierra Partnership 2010), indicating that lodgepole pine and possibly other subalpine conifers will be more prone to climate change impacts toward the southern end of its geographic distribution. Projected declines are also anticipated for western white pine in the Sierra Nevada, although suitable climate space is projected to increase approximately 160 and 330 m in elevation for western white pine and whitebark pine, respectively (Richardson et al. 2008).

Projected future climate vulnerability of Clark's nutcracker in the Sierra Nevada under the GFDL climate model (Siegl et al. in review) suggests potential indirect negative impacts of climate change on subalpine tree species. Whitebark pine, limber pine, and bristlecone pine are especially dependent on Clark's nutcracker for seed dispersal and colonization of unoccupied sites (Table 2; Coop and Schoettle 2009, Lanner 1988, Tomback 1982). Consequently, the loss or reduction of Clark's nutcracker populations in high-elevation forests may limit localized dispersal potential and further exacerbate future environmental conditions for these high-elevation white pine species. Additionally, severe, climate-induced mortality in white pine stands (similar to that observed in stands heavily impacted by white pine blister rust) may induce increased seed predation by Clark's nutcracker, resulting in heavily reduced dispersal potential and regeneration densities (McKinney and Tomback 2007). Alternatively, potential upslope movement of Clark's nutcracker could facilitate the migration of these white pines species to higher elevations or other future suitable habitats. Understanding future range shifts resulting from climate change will require careful consideration of altered species interactions (Van der Putten et al. 2010).

Schwartz et al. (2013) used a climatic envelope modeling approach based on two GCMs (PCM, GFDL) and two climate surface models (ensemble of Bioclim and Flint Regional Water Balance model; downscaled to 270 m) to evaluate the exposure of subalpine forest and individual subalpine tree species (e.g., whitebark pine, foxtail pine, lodgepole pine) to climate change in the southern Sierra Nevada. Their results indicate that by the end of the century subalpine forests will be highly to extremely vulnerable (outside the 90th percentile of the current bioclimatic distribution for the vegetation type) in 72% (PCM) or 95% (GFDL) of subalpine forests and 56% (PCM) and 83% (GFDL) of whitebark pine forests in the southern Sierra Nevada national forests (Sequoia, Sierra, and Inyo National Forests and southern half of the Stanislaus National Forest; Figure 15). The total area of low climate exposure for subalpine forests in the southern Sierra Nevada will only be 18% (PCM) and 0% (GFDL) by the end of the century; values for foxtail pine, whitebark pine, and lodgepole pine reflect these trends (Table 8). By the end of the century, geographic areas of low climate exposure (i.e., climatic refugia) for subalpine forests under the PCM model are generally scattered along the higher elevations within the entire study area, with core areas of low exposure in: (1) the central portion of the Inyo National Forest, and (2) eastern portions of Sierra National Forest and Sequoia, Kings Canyon, and Yosemite National Parks (Figure 16). Under the GFDL model, climatic refugia are primarily limited to the highest elevations of Sequoia and Kings Canyon National Parks (especially in the Kern River drainage) and Sierra and Inyo National Forests (Figure 17). End-of-century climate projections suggest high degrees of climate exposure and pronounced range reductions for subalpine conifers in the southern Sierra Nevada (Schwartz et al. 2013). Climate model forecasts for the state of California suggest that these drastic reductions in subalpine forests may occur across the entire assessment area.

Based on these collective modeling results, most subalpine forests in the assessment area will be outside its historic and contemporary climate envelope by the end of the century. Projected changes in the distribution of subalpine forests consistently show a pronounced reduction in their geographic extent within the assessment area by 2070–2100. Several models also project a relatively high degree of climate vulnerability for subalpine forests within the southern extent of its geographic distribution, at lower elevations, and within isolated populations. These projections support theoretical models that predict greater loss of populations at geographic range margins and low latitude limits (Hampe and Petit 2005). Ultimately, the degree of climate vulnerability in subalpine conifers will be contingent on several factors not covered by most species distribution models, including migration rates, biotic interactions, evolutionary processes (e.g., adaptation, genetic drift), physiological tolerances, edaphic constraints, and interacting stressors (Clark et al. 2011, Kuparinen et al. 2010, Rowland et al. 2011, Zhu et al. 2012).

SUMMARY

- Comparisons between historic and current conditions indicate that modern subalpine stands of the assessment area are largely within the natural range of variation with respect to their composition, structure, and function (Table 9).
- Exceptions include an increase in total tree densities (especially in the small size classes), considerable shift in the tree size class distribution to smaller diameters, change in tree spatial distribution, and a decrease in the density of large-diameter subalpine trees such as lodgepole pine and western white pine. These changes have likely occurred primarily as a result of 19th century logging within secondary-growth stands and recent climatic warming within the entire assessment area.
- Fire regimes in subalpine forests have not changed significantly. However, fire return intervals and fire rotations have generally lengthened during much of the 20th century due to fire suppression activities, and total burned area has increased since 1984 in several subalpine forest types. Moreover, future fire frequency, annual burned area, and fire severity are projected to increase in subalpine forests with climate change.
- Mountain pine beetle outbreaks likely have not changed considerably during historic (1890–1960) and contemporary (1961–2005) periods. However, future projections and recent beetle eruptions in subalpine forests (especially 2006–2012) suggest increased potential for large-scale outbreaks over the next 50 years that will exceed the historic range of variation.
- Treeline growth and recruitment of some subalpine species, such as bristlecone pine, have increased beyond the historic range of variation within the past 40 to 50 years, likely owing to increases in temperature.
- Climate envelope models consistently project substantial future loss (average: 85%) or high climate vulnerability of subalpine forests in the assessment area by the end of the century. This suggests that the greatest changes in subalpine forests during the 21st century will occur as a consequence of climate change.

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TABLES

Table 1. Climate characteristics of subalpine forests in the assessment area. Snow variables are primarily based on April 1st averages.

Climate Variable	Average (Subregion)[1]
Annual Precipitation (mm)	750–1250 (Sierra Nevada) 320 (White and Inyo Mountains)
Precipitation as Snow (%)	70–99%
Mean Snow Depth (cm)	160 (Southern) 210 (Northern)
Maximum Annual Snow Depth (cm)	140–500
Snow Water Equivalent (mm)	50–160 (Southern) 70–190 (Northern)
Months of Maximum Snow Depth	Early to late April
Snowpack Duration (days)	>200
Daily Snow-Covered Area (3000 m elev.) (%)	70
Mean Winter Temperature (° C)	-4
Mean Summer Temperature (° C)	12
January Minima (° C)	-11
July Maxima (° C)	16
Growing Season Length (weeks)	8
Lightning (strikes/year/100 km^2)	33.6

[1] Data sources include Potter (1998, 2005), Rundel et al. (1988), Fites-Kaufman et al. (2007), Agee (1993), Barbour et al. (2002), Jepsen et al. (2012), Lloyd and Graumlich (1997), Munz and Keck (1959), NOAA (2013), Rice et al. (2011), van Wagtendonk and Cayan (2007), van Wagtendonk and Fites-Kaufman (2006).

Table 2. Characteristic ecological features of subalpine conifers in the Sierra Nevada[1].

Feature	Whitebark Pine	Foxtail Pine	Limber Pine	Bristlecone Pine	Western White Pine	Lodgepole Pine	Mountain Hemlock
Topographic, Soil, and Microclimate Associations	Harsh, cold, dry slopes	Cool and dry sites on well-drained, decomposed granite soils	Dry, steep, and rocky slopes with well-drained soils	Limestone, low nutrient soils on dry sites	Sunny sites with unfertile and shallow soils	Hydric (meadows) to moderately xeric, post-fire environments	Moist and cold sheltered canyons, ravines, and lake benches
Sites of Successional Replacement[2]	Productive sites at lower elevation	Mesic and productive sites	Mesic sites	Mesic and productive sites	Productive sites	Productive sites at lower elevation	Post-fire environments
Shade Tolerance	Moderate	Intolerant	Intolerant	Intolerant	Intolerant	Moderate	High
Fire tolerance	Some fire adaptations Post-fire colonizer	Fire avoider	Fire avoider	Fire avoider	Some fire adaptations Post-fire colonizer	Fire sensitive Post-fire colonizer but cones not serotinous	Fire avoider
Spatial pattern	Clustered	Single stem	Clustered	Clustered	Both	Single Stem	Single Stem
Primary seed dispersal agent[3]	Animal	Unknown	Animal	Animal and wind	Animal and wind	Wind and animal	Wind

1 Data sources include: Agee (1993), Beasley and Klemmendson (1973, 1976, 1980), Billings and Thompson (1957), Bunn et al. (2005), Burns and Honkala (1990), Caprio (2006, 2008), Coop and Schoettle (2009), Ernst et al. (2003), Fites-Kaufman et al. (2007), Harris (1939), Hiebert and Hamrick (1984), Keane et al. (2012), Keifer (1991), Lanner (1988), Lanner et al (1984), Maloney et al. (2011), Parker (1986, 1988), Pierce and Taylor (2011), Potter (1994, 1998), Rourke (1988), Rundel et al. (1988), Sawyer et al. (2009), Taylor (1995), Tomback (1982), Vankat (1970), Tomback et al. (1993), Vander Wall (2008), van Wagtendonk and Fires-Kaufman 2006, and Wright and Mooney (1965).

2 Indicates environments where species may establish and grow but are either replaced by more competitive species over time or are less suited at exploiting early seral environments (e.g., mountain hemlock).

3 Animal dispersed seed are mainly due to the seed caching activity of Clark's nutcracker, but may include significant dispersal by chipmunks and squirrels. Seed dispersal mechanisms in foxtail pine are poorly understood but currently assumed to be primarily wind dispersed.

Table 3. General overview of climate, vegetation, and environmental conditions during the Holocene in the higher elevations of the Sierra Nevada.

Time Period	Years Before Present	Climate conditions	Vegetation and Environmental Changes
Early Holocene	16,000 to 10,000	Cooler and moister	Open pine forests mixed with mountain hemlock and Sierra juniper Higher montane lake levels Lower fire frequencies in montane forests
Mid-Holocene Xerothermic (Hypsithermal)[1]	8000 to 5000 (or 4000)	Warmer (~1° C) and episodically drier	Open pine forests with shrub understory dominate Red and white fir, mountain hemlock, and subalpine conifers (whitebark pine, lodgepole pine) restricted to mesic sites Montane lake levels drop Substantial increase in fire frequencies in montane forests
Late Holocene	4000 to 1100	Relatively cooler and often moister	Red and white fir, mountain hemlock, and subalpine conifers increase Lake levels increase Decreased fire frequencies in montane forests
Medieval warm period[1]	1100 to 650	Warmer (~0.25 ° C) and often drier	Some increase in tree establishment of subalpine conifers at treeline Lake levels moderately decrease Modest increase in fire frequencies in montane forests
Little Ice Age	650 to 100	Cooler and moister	Downslope movement of upper elevation limit of red fir
Current (20^{th} century)	100 to 0	Relatively cool and moist conditions with recent increases in temperatures during past three decades	Era of modern fire suppression and land management practices in montane forests

[1] Periods that may serve as possible analogues for climate in the near future.

Table 4. Variables lacking adequate historic records to quantify historic range of variation.

Variable	Issue	Surrogate information source
Landscape and regional scale patterns of disturbance (e.g., fire, insects, disease)	Historic information limited, especially prior to 20th century	Contemporary reference sites, limited historic accounts
Historic vegetation spatial structure (two and three dimensional), including structural complexity	Information rarely or not collected in historic (early 20th century) forest inventories and surveys; primarily available recently with sufficient technology (e.g., LiDAR)	Contemporary reference sites; limited historic information on tree spatial aggregation; limited historic accounts
Understory vegetation composition and soil cover (litter, duff, bare mineral soil, coarse woody debris)	Limited information in historic forest inventories and surveys; no information prior to widespread sheep grazing in the early 1860s except in few stratigraphic pollen records	Contemporary reference sites
White pine blister rust and other non-native species	Most species introductions to subalpine forests have been recent and are not within the scope of this NRV assessment	Not applicable
Air quality	Historic information lacking	No available sources prior to 1870
Snags and logs	Historic information lacking	No available sources
Nutrient cycling rates and biomass	Historic information lacking	Contemporary reference sites
Connectivity	Historic and contemporary information lacking except for biogeographic isolation from other regions	No available sources
Grazing	Historic information limited or lacking	Limited historic accounts
Large-scale (landscape, regional) fire severity, vegetation productivity, and other processes that require remote-sensing based measures	No information prior to availability of satellite-derived information (pre-1984)	Contemporary reference sites
Metapopulation dynamics	Historic and contemporary information lacking	No available sources

Table 5. Historic Fire Return Interval (FRI) estimates for subalpine forests in the Sierra Nevada.

Vegetation Type	Subregion	Mean FRI	Median FRI	Min. FRI	Max. FRI	Years Sampled	Sample Type[1]	Reference
Subalpine	State of California	113	132	100	420	—	—	Van de Water & Safford (2011)
Western white pine	State of California	50	42	15	370	—	—	Van de Water & Safford (2011)
Lodgepole pine	State of California	37	36	15	290	—	—	Van de Water & Safford (2011)
Lodgepole pine	Northern	—	37	6	48	1650–1883	Comp.	Bekker & Taylor (2001)
Lodgepole pine	Northern	43	48	—	—	—	—	Bekker & Taylor (2010)
Lodgepole pine	Northern	67	—	—	—	1735–1929	Comp.	Taylor & Solem (2001)
Subalpine[2]	Central (Western)	—	230	40	290	500 BC–1985	Paleo.	Hallett & Anderson (2010)
Subalpine[2]	Central (Eastern)	—	105	30	135	500 BC–1985	Paleo.	Hallett & Anderson (2010)
Lodgepole pine	Southern	102	—	4	163	—	—	van Wagtendonk et al. (2002)[3]
Subalpine	Southern	187	—	—	508	—	—	Caprio & Lineback (2002)[4]
Lodgepole pine	Southern	50	—	31	98	1455–1860	Comp.	Caprio (2008)
Bristlecone pine	Eastern (Southern)	46	—	—	—	1460–1871	Comp.	North et al. (2009)[4]
Bristlecone pine	Eastern (Southern)	143	—	—	—	1500–1850	—	Richardson & Howell (2005)
Foxtail pine	Eastern (Southern)	28	—	—	—	1578–2008	Comp.	North et al. (2009)[5]
Foxtail pine	Southern	250	—	—	—	1578–2008	Comp.	Stephenson et al. (2005)
Lodgepole–Foxtail pine	Eastern (Southern)	39	—	—	—	1490–2008	Comp.	North et al. (2009)[5]
Lodgepole pine	Eastern (Southern)	19	—	—	—	1676–2006	Comp.	North et al. (2009)[5]
Whitebark pine	Central Cascades	85	—	—	—	—	—	Murray (2007)
Whitebark–Lodgepole pine	Central Cascades	73	—	—	—	—	—	Murray (2007)

Subalpine type/group (aggregation)	Mean FRI	Median FRI	Min. FRI	Max. FRI	No. of studies	Subregions
Lodgepole pine	43	56	14	150	7	Northern, Southern, Eastern
Subalpine	160	156	57	338	4	Central, Southern, Eastern, State of California
Red fir–Western white pine–Mountain hemlock[6]	83	66	18	78	4	Northern

[1] Refers to whether estimates were derived from a single tree sample or composite (Comp.) sample, or were estimated using paleofire reconstruction methods (Paleo.). Sample areas in FRI studies were nearly all less than 2 ha in size, with a few exceptions (e.g., 18–44 ha in North et al. 2009).

[2] Contemporary subalpine forest site included the following dominant species at the central site: lodgepole pine, mountain hemlock, red fir, and limber pine. Species at the eastern site included: lodgepole pine, mountain hemlock, western white pine, and whitebark pine.

[3] Values from van Wagtendonk et al. (2002) were extracted from Caprio and Lineback (2002) and other sources from sites primarily in the southern Sierra Nevada.

[4] FRI estimates based primarily in foxtail pine and whitebark pine stands of Sequoia National Park. Mean maximum FRI was calculated using a randomization algorithm drawing from the pooled fire chronology data from a specific collection site to yield a more conservative estimate than the mean

[5] The larger survey area for North et al. (2009) likely resulted in a relatively low FRI estimate, especially for foxtail pine and bristlecone pine stands where mean reference (historic) FRI estimates based on other sources are 250 years for foxtail pine and 143 years for bristlecone pine in the assessment area.

[6] Fire return interval estimates extracted from Red fir NRV chapter for comparison

Table 6. Proportion of fire severity classes in Sierra Nevada subalpine forests based on historic and contemporary reference site information.

Forest type	Location	Unchanged/ Unburned (%)	Low Severity (%)	Moderate Severity (%)	High Severity (%)	Reference
Lodgepole pine	Southern Cascades	—	8	17	75	Taylor & Solem (2001)[1]
Lodgepole pine–red fir	Southern Cascades	—	10	52	38	Taylor & Solem (2001)[1]
Red fir–western white pine	Southern Cascades	—	33	48	19	Taylor & Solem (2001)[1]
Lodgepole pine – 1st burn	Yosemite NP	28	56	15	<1	van Wagtendonk et al. (2012)
Lodgepole pine – 2nd burn (reburn)	Yosemite NP	7	24	46	23	van Wagtendonk et al. (2012)
Whitebark pine–mountain hemlock	Yosemite NP	70	27	3	0	Thode et al. (2011)[2]
Lodgepole pine	Yosemite NP	25	30	37	8	Thode et al. (2011)[2]
Lodgepole pine	Kings Canyon NP	—	75	23	2	Caprio (2006)
LANDFIRE Biophysical Setting Model[3]:						
Mountain hemlock–lodgepole pine–red fir	Sierra Nevada	—	0	36	64	van Wagtendonk et al. (2005)
Whitebark pine–mountain hemlock–red fir	Southern Sierra Nevada	—	0	50	50	Stephenson et al. (2005)
Bristlecone and limber pine	White & Inyo Mountains	—	29	—	71	Richardson & Howell (2005)
Lodgepole pine (wet)	Sierra Nevada	—	71	7	22	Caprio (2005a)
Lodgepole pine (dry subalpine)	Sierra Nevada	—	45	45	11	Caprio (2005b)
Aggregation/Group[4]	Locations	Unchanged (%)	Low (%)	Moderate (%)	High (%)	Number of Studies
Lodgepole pine	Multiple	19	29	28	24	5
Other Subalpine	Multiple	52	22	19	7	2

[1] Based on historic reference information.

[2] Fire severity estimates are approximated.

[3] Based on LANDFIRE Biophysical Setting Model estimates of historic reference conditions.

[4] Fire severity averages are adjusted such that sum of fire severity classes for each group equals 100%. Averages do not include LANDFIRE Biophysical Setting Model estimates.

Table 7 – Growth and tree recruitment relationships with climate in subalpine forests near treeline or ecotonal boundaries in the assessment area.

Subalpine Species (Region)	Climate Relationship(s)	Reconstruction Period (years)	Reference(s)
Bristlecone pine (White Mountai ns)	Increase in tree growth at treeline positively associated with increased temperature and weakly associated with precipitation. Growth in lower-elevation sites negatively associated with increased temperature and decreased precipitation.	3700	Salzer et al. (2009)
Foxtail pine (Southern Sierra)	Decreased tree recruitment and density and treeline elevation associated with multi-decadal droughts coupled with warmer temperatures, implicating the importance of water balance relationships.	1000–3500	Lloyd & Graumlich (1997), Lloyd (1997)
Foxtail pine (Southern Sierra)	Tree growth and recruitment positively associated with temperature in relatively mesic plots but positively correlated with precipitation in relatively xeric plots.	600	Bunn et al. (2005)
Foxtail pine (Southern Sierra)	Tree growth limited by drought stress in years of low precipitation and cool temperatures limit growth during high winter precipitation years.	850	Graumlich (1991)
Lodgepole pine (Southern Sierra)	Tree growth positively correlated with winter precipitation and secondarily by summer temperature, with optimal growth during moderate temperatures coupled with high precipitation.	400	Graumlich (1991)
Mountain hemlock (Southern Cascades)	Tree expansion into previously unoccupied higher-elevation sites positively associated with increased temperature, lower snowpack, and periods of higher moisture.	150	Taylor (1995)
Whitebark pine, Western white pine, Lodgepole pine (Eastern Sierra)	Annual branch growth and invasion of snowfields positively associated with increased minimum temperature and Pacific Decadal Oscillation index.	100	Millar et al. (2004)

Table 8 – Projected future changes in the distribution of subalpine forests and tree species based on climate envelope (species distribution) and dynamic vegetation (MC1) models. Percent decrease or stable indicates the percent change in the area covered by subalpine conifers within the geographic scope and time period of each study. GCMs primarily include PCM (warmer and similar precipitation) and GFDL (hotter and drier).

Unit of analysis	Geographic scope	GCM and trends (model type)	Decrease (%)	Stable (%)	Time Period	Reference
Subalpine and alpine[1]	California	PCM (MC1)	55	—	2071-2100	Lenihan et al. (2008)
Subalpine and alpine[1]	California	GFDL (MC1)	77	—	2071-2100	Lenihan et al. (2008)
Subalpine	Southern Sierra Nevada	Ensemble	78 (11)[2]	22 (89)[2]	2071-2100	Gonzalez[3] (2012)
Bristlecone pine	White and Inyo Mountains	Ensemble[3]	75–99%	1–25	2071-2100	Van de Ven et al. (2007)
Lodgepole pine[4]	Southern Sierra Nevada	Ensemble	26	60	2040-2065	SSP (2010)[3]
Lodgepole pine[5]	California	Ensemble	58	34	2040-2065	SSP (2010)[3]
Lodgepole pine[6]	Southern Sierra Nevada	PCM (Bioclim, Flint)	96	4	2070-2099	Schwartz et al. (2013)
Lodgepole pine[6]	Southern Sierra Nevada	GFDL (Bioclim, Flint)	100	0	2070-2099	Schwartz et al. (2013)
Subalpine conifer forest[6]	Southern Sierra Nevada	PCM (Bioclim, Flint)	82	18	2070-2099	Schwartz et al. (2013)
Subalpine conifer forest[6]	Southern Sierra Nevada	GFDL (Bioclim, Flint)	100	0	2070-2099	Schwartz et al. (2013)
Foxtail pine[6]	Southern Sierra Nevada	PCM (Bioclim, Flint)	83	17	2070-2099	Schwartz et al. (2013)
Foxtail pine[6]	Southern Sierra Nevada	GFDL (Bioclim, Flint)	100	0	2070-2099	Schwartz et al. (2013)
Whitebark pine[6]	Southern Sierra Nevada	PCM (Bioclim, Flint)	82	18	2070-2099	Schwartz et al. (2013)
Whitebark pine[6]	Southern Sierra Nevada	GFDL (Bioclim, Flint)	100	0	2070-2099	Schwartz et al. (2013)
Whitebark pine	Entire species' range	Unknown	97	3	2090	Warell et al. (2007)

Whitebark pine	Southern Sierra Nevada	Canadian Center for Climate Modeling GCM	99.97	0.03	2060-2090	Anderson et al. (2012)

Averages across studies and GCMs for end of century (2071–2100) projections:

Forest Type or Species	Decrease	Stable	Number of Studies
Subalpine forest	78	12	3
Whitebark pine	95	5	3
All subalpine conifer vegetation types	85	15	5

[1] Projections are pooled for subalpine forest and alpine biomes.

[2] Values in parentheses indicate % change in subalpine forests of the White and Inyo Mountains and Glass Mountain.

[3] Specific GCMs were not provided, but estimates were based on projected temperature increases (3 to 5° C) from Hayhoe et al. (2004), Lenihan et al. (2003), and other sources.

[4] Estimates for percent stable and percent increase ("percent remaining") are pooled.

[5] Decrease is defined as percentage of subalpine conifer distribution that is "stressed." Projected estimates also include an uncertain category defined as areas lacking model agreement (range: 7–12%). Reference refers to the Southern Sierra Partnership (2010).

[6] Based on U.S. Forest Service Region 5 Calveg subalpine conifers or whitebark pine alliance vegetation types. Percent decrease estimate includes moderate, high, and extreme climate exposure categories (outside 66th percentile bioclimatic distribution), and percent stable estimate is equal to the percentage in the low exposure category (inside the 66th percentile bioclimatic distribution). Projection estimates are based on subalpine forests on national forest lands of the southern Sierra Nevada (Inyo, Sequoia, and Sierra national forests and southern half of Stanislaus National Forest).

Table 9 – Deviations from the Natural Range of Variation (NRV) based on historical and modern reference information in Sierra Nevada subalpine forests. Changes in variables resulting from projected future changes in climate are also provided for comparison.

Variable(s)	Historic Reference Period	Within NRV	Direction of Departure	Confidence	Notes	Pages in Discussion
Fire Return Interval	1580–1942 (primarily before 1900)	Yes	Future decreases (i.e., increases in fire frequency)	Moderate	Likely within NRV for nearly all subalpine forest types except lodgepole pine forest; Projected future range of variation will exceed NRV for all subalpine forest types	Pg. 6–7 Table 5 Fig. 3
Fire Rotation	1650–1905	Yes	Future decreases (i.e., increases in fire frequency)	Moderate	Likely within NRV but projected future range of variation will exceed NRV	Pg. 7
Fire Size	1729–1918	No	Increasing	Moderate	NRV departure likely due to recent changes in climate	Pg. 8 Fig. 4, 5
Fire Type	1625–1845	Yes	—	Moderate	Refers to the dominant patterns in and controls over fire behavior within a vegetation type	Pg. 8–9
Fire Seasonality	1650–1942	Yes	—	High	—	Pg. 9
Fire Severity	1650–1930	Yes?	—	Low	Current fire severity trends are unclear due to insufficient data	Pg. 9–10 Table 6 Fig. 6
High Severity Fire Patch Size and Size Distribution	Late 1800s	Yes	—	Low	Limited historic information	Pg. 10–11
Insects – Mountain Pine Beetle	1895–1960	Yes	Future increases for whitebark, limber, lodgepole, and western white pines	Low to Moderate	Likely within NRV but projected future range of variation will exceed NRV. Current period refers to years preceding recent beetle outbreaks in the assessment area (1961–2005).	Pg. 11–12 Fig. 7
Wind and Volcanism	Variable	Yes	—	Low	Refer to Red Fir NRV	—
Climatic Water Deficit	1700	Yes	Future increases	Low	Likely within NRV but projected future range of variation may exceed NRV	Pg. 13 Fig. 8

Tree Growth and Recruitment at Treeline	1500 B.C.–1960 A.D.	Yes/ No	Variable but increasing for most species, such as bristlecone pine	High	NRV departure due to recent changes in climate. There is a recent trend toward increased growth and recruitment at treeline that is either approaching the upper limit or exceeding the NRV	Pg. 13 Table 7
Total Tree Densities (all size classes)	1870–1928	No	Increasing	Moderate	NRV departure due to recent changes in climate and 19th century logging in secondary-growth stands	Pg. 13–14 Fig. 10, 11
Average Tree Diameter and Density of Large Diameter Trees	1870–1928	No	Moderate	Decreasing	NRV departure due to recent changes in climate and 19th century logging in secondary-growth stands	Pg. 13–14 Fig. 10, 11
Tree Size Class Distribution	1870–1928	No	Shifting to Smaller Size Classes	Moderate to High	Same as above	Pg. 13–14 Fig. 9, 12
Basal Area	1870–1928	Yes	—	Moderate	—	Pg. 14 Fig. 11
Tree Spatial Patterns and Structural Diversity	1600–1870	No	Non-directional pattern in tree spatial patterns	Low	Current unlogged stands similar to NRV, but lower structural diversity in current stands exposed to 19th century logging	Pg. 14–15 Table 2 Fig. 2b, 12
Canopy Structure (canopy height, base height, and bulk density)	1600–1870	Yes/ No	Lower canopy base height	Low	Based on Taylor et al. in press for lodgepole pine stands	Pg. 15
Understory Plant Cover	1600–1940	Yes	—	Low	—	Pg. 15-16
Seral Class Proportions	1600–1860	Yes/ No	Greater proportion of early-seral class in lodgepole pine–dry forest	Low	Based on LANDFIRE Biophysical Settings Modeling for Stanislaus National Forest only; Marginal changes for subalpine forest not dominated by lodgepole pine	Pg. 16 Fig. 13, 14
Tree Species Composition	1870–1928	Yes	—	High	Based on relative abundance of subalpine tree species	Pg. 16–17 Fig. 12
Projected Future Distribution	2010–2099	—	Future contraction of geographic range and increased climate vulnerability	Low to Moderate	Confidence in future projections is low especially at later time intervals, but confidence in the overall degree of projected vulnerability is moderate	Pg. 17–18 Table 8 Fig. 15–17

FIGURES

Figure 1 - Distribution map of subalpine conifers in the assessment area.

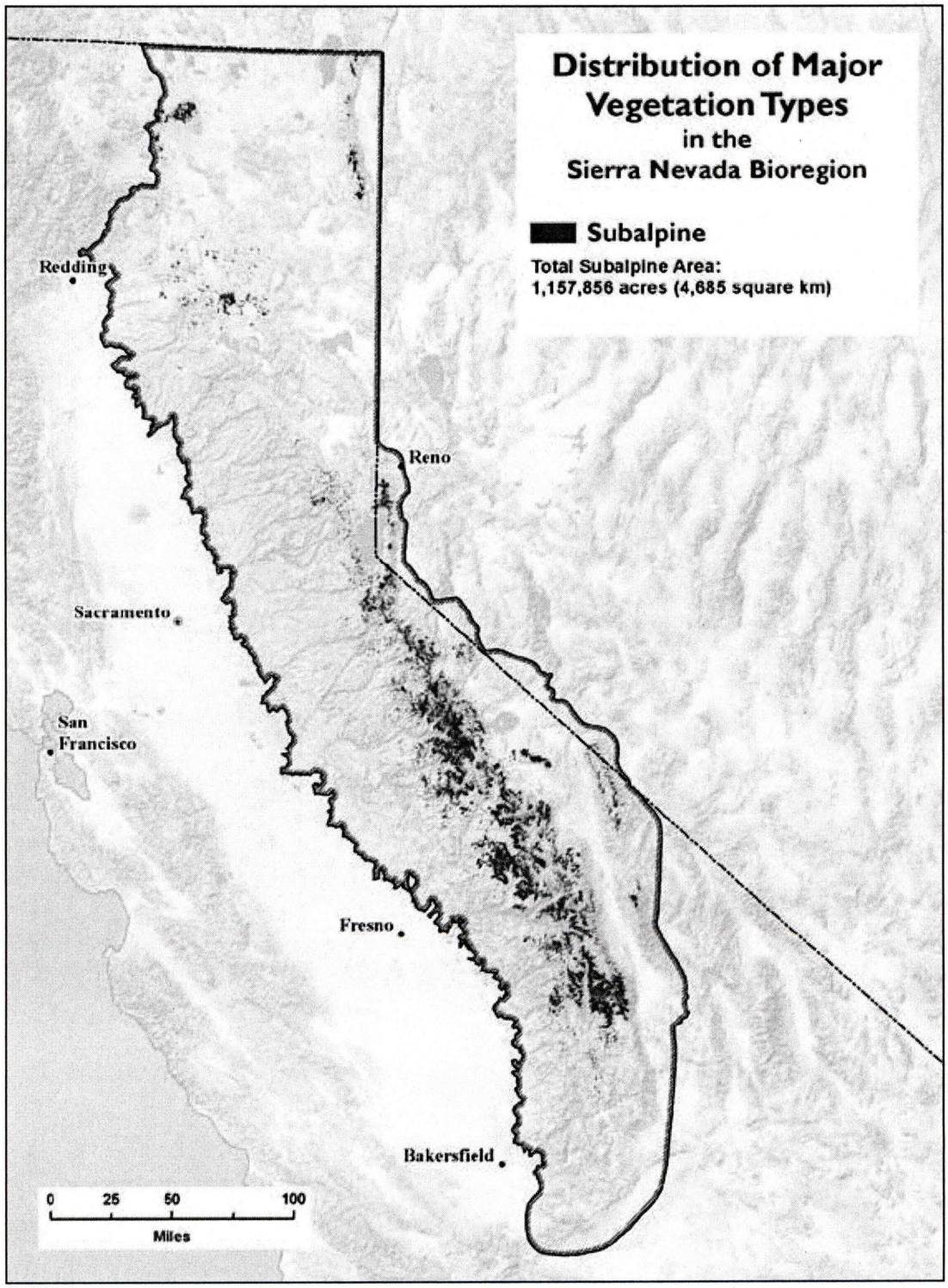


Figure 2a – Photos of subalpine forests in the Sierra Nevada, including lodgepole pine and western white pine forest (top photo), lodgepole pine and mountain hemlock forest (middle photo), and high-elevation landscape dominated by whitebark pine and lodgepole pine with limber pine situated on steeper slopes (bottom photo). Top photos were taken in the Ansel Adams Wilderness of the Sierra National Forest. Bottom photo was taken in the John Muir Wilderness of the Inyo National Forest. Image Credit: Marc Meyer, USFS.

Figure 2b – Photos of foxtail pine forests in the southern Sierra Nevada, Sequoia National Park. Image Credit: Tony Caprio, National Park Service.

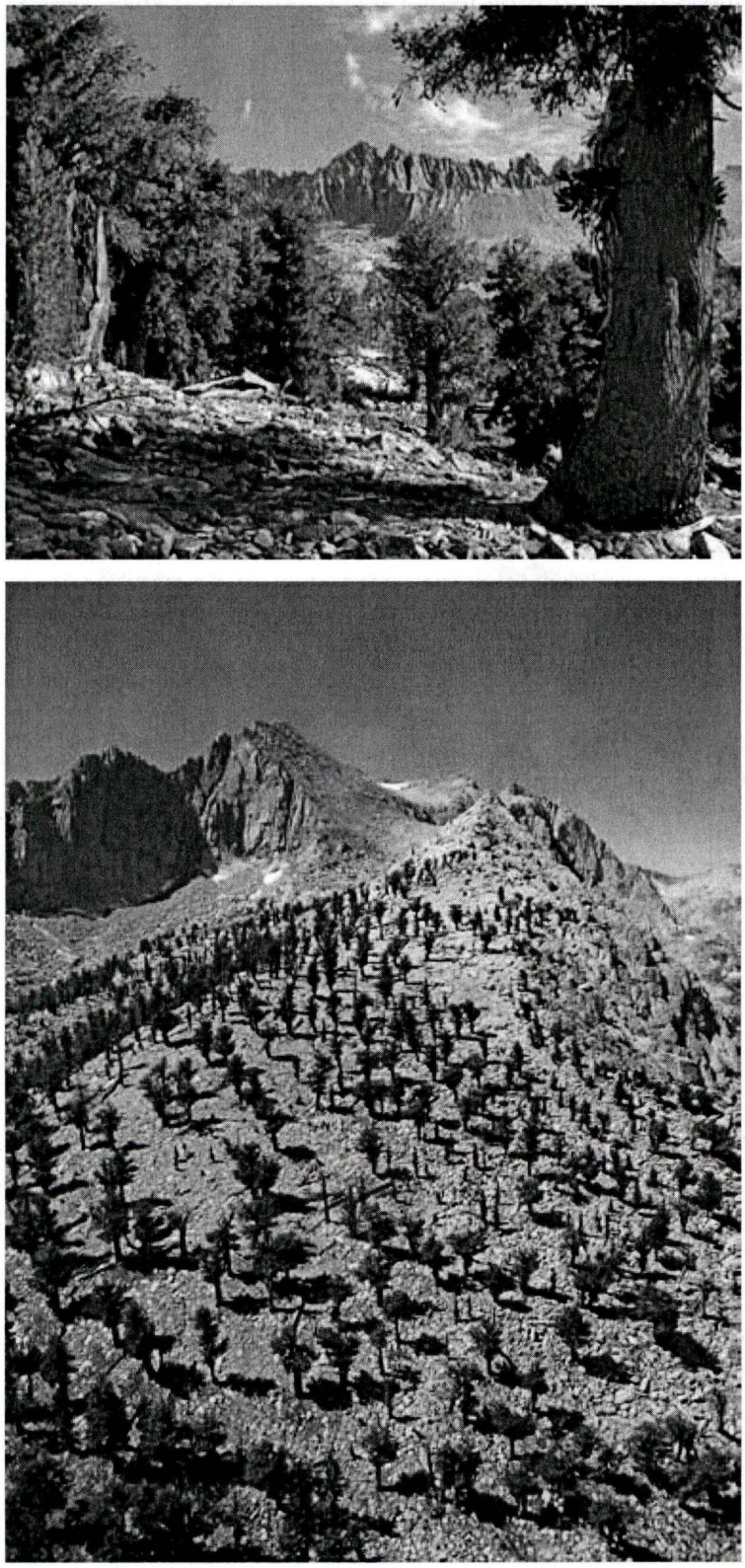


Figure 3 – Projected increase in fire probability for subalpine forests in the southern Sierra Nevada under the GFDL (warmer-drier) and PCM (warmer-wetter) climate models by the end of century (2070–2099). Frequency distributions represents future projected (red, green) and current (gray) climate conditions. Y-axis represents the number of model simulations. Model projections based exclusively on the Subalpine Conifers Calveg type. Graphics courtesy of Moritz et al. (2013).

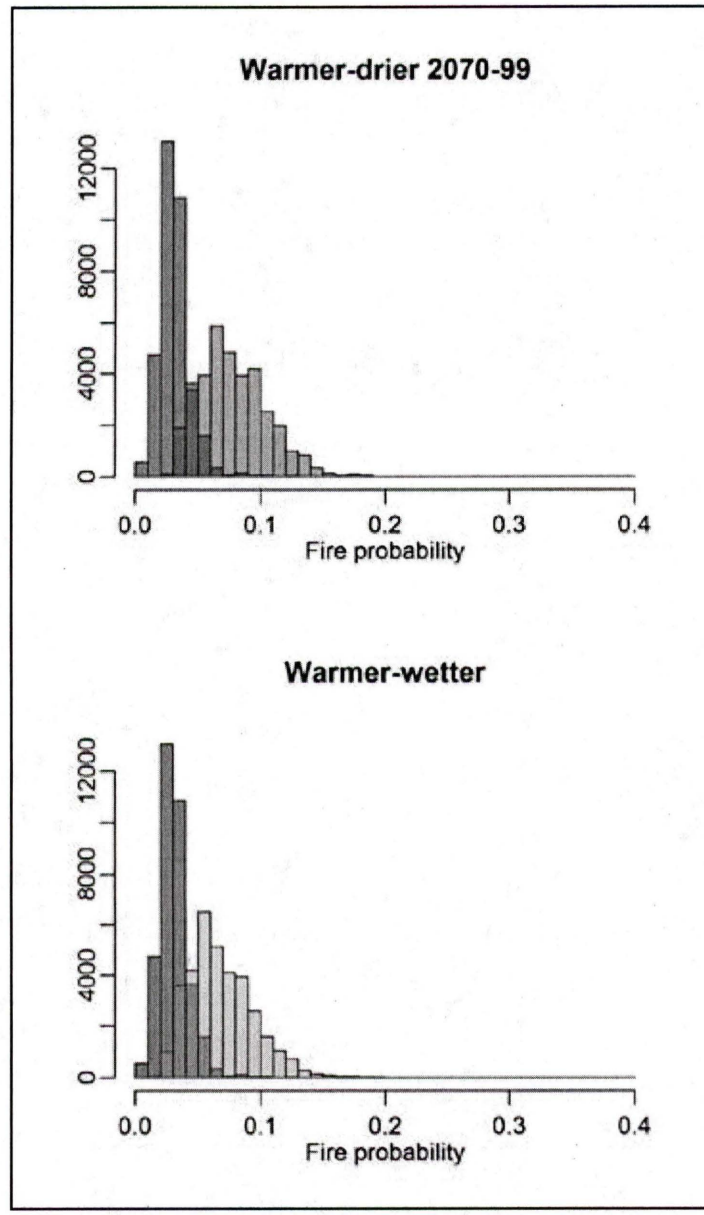


Figure 4 – Percent of lightning-ignited fires by size class in red fir and lodgepole pine forests of Yosemite National Park, 1972–1993. Figure redrawn from van Wagtendonk (1993) and Potter (1998).

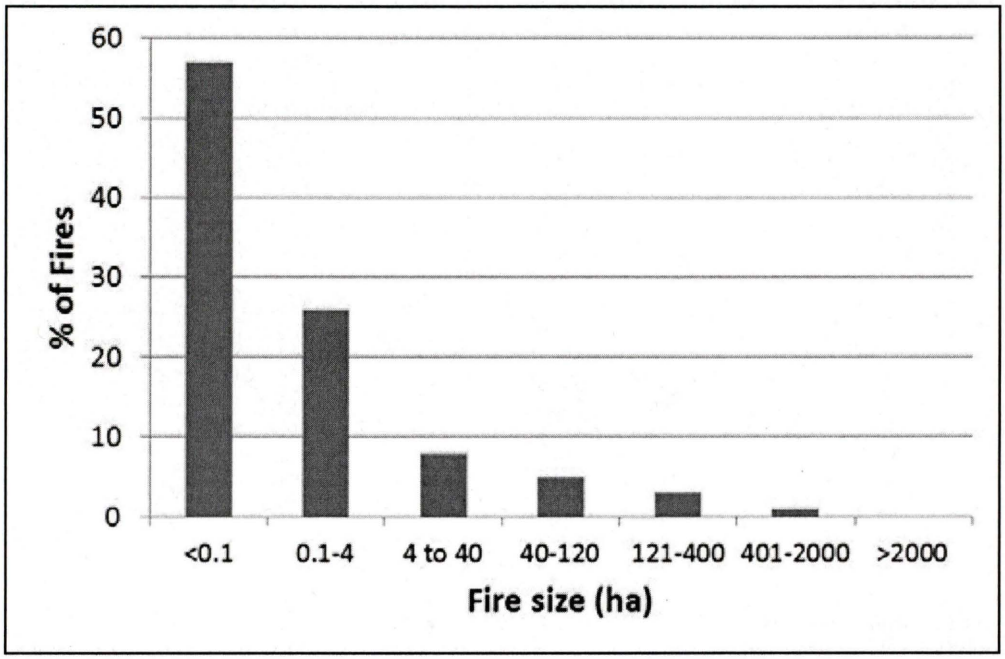


Figure 5 – Percent of total area burned by fire size class in red fir and lodgepole pine forests of Yosemite National Park, 1972–1993. Figure redrawn from van Wagtendonk (1993) and Potter (1998).

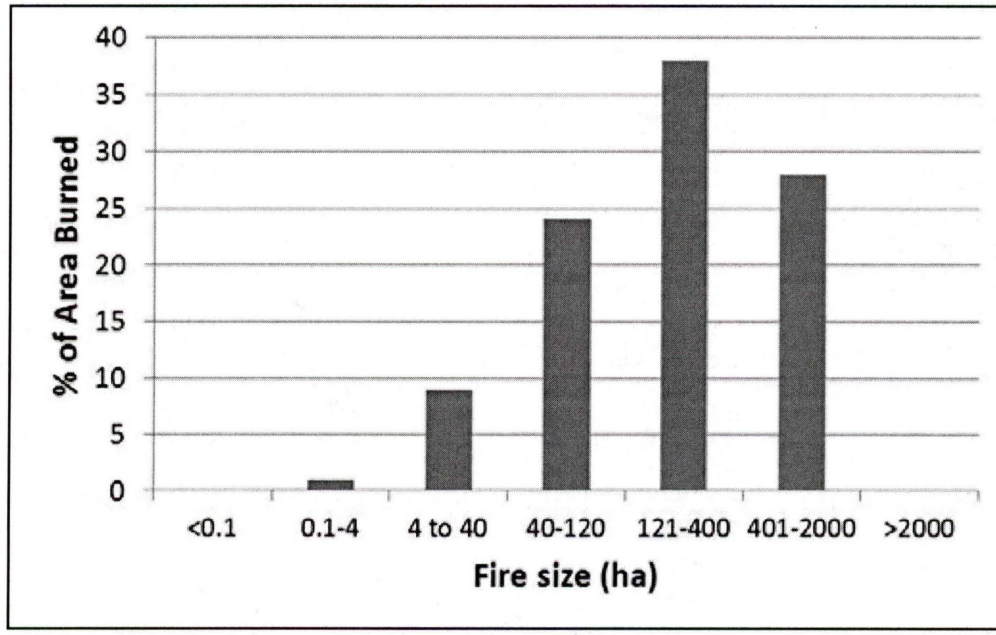


Figure 6 – Photo of a high severity burned patch in a lodgepole pine forest in the Illilouette Creek Basin, Yosemite National Park. Photo was taken approximately eight years following the Meadow Fire (2004). Image Credit: Marc Meyer, USFS.

Figure 7 – Area of mountain pine beetle adaptive seasonality from 1895 to 2100 in subalpine forests (3000–3500 m elevation) of the western United States, including the Sierra Nevada. Time periods include historical (1895–1960), current (1961–2005), and future projection under warming climate (2006–2100). Adaptive seasonality is an estimate of the synchronous and successful emergence of adult beetles and is closely associated with outbreaks. Figure redrawn from Hicke et al. (2006).

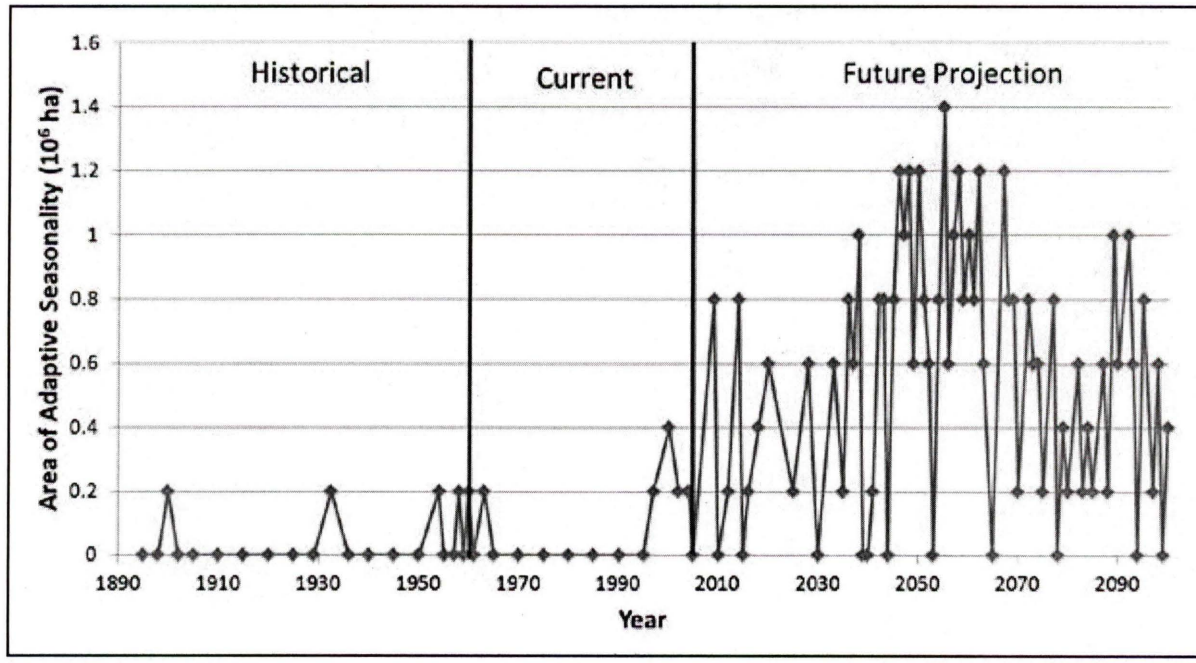


Figure 8 – Mean values of climatic water deficit for modeled climate in the past (~1700; Little Ice Age), present (1971-2000), and near future (2020-2049). Data source is Lutz et al. (2010).

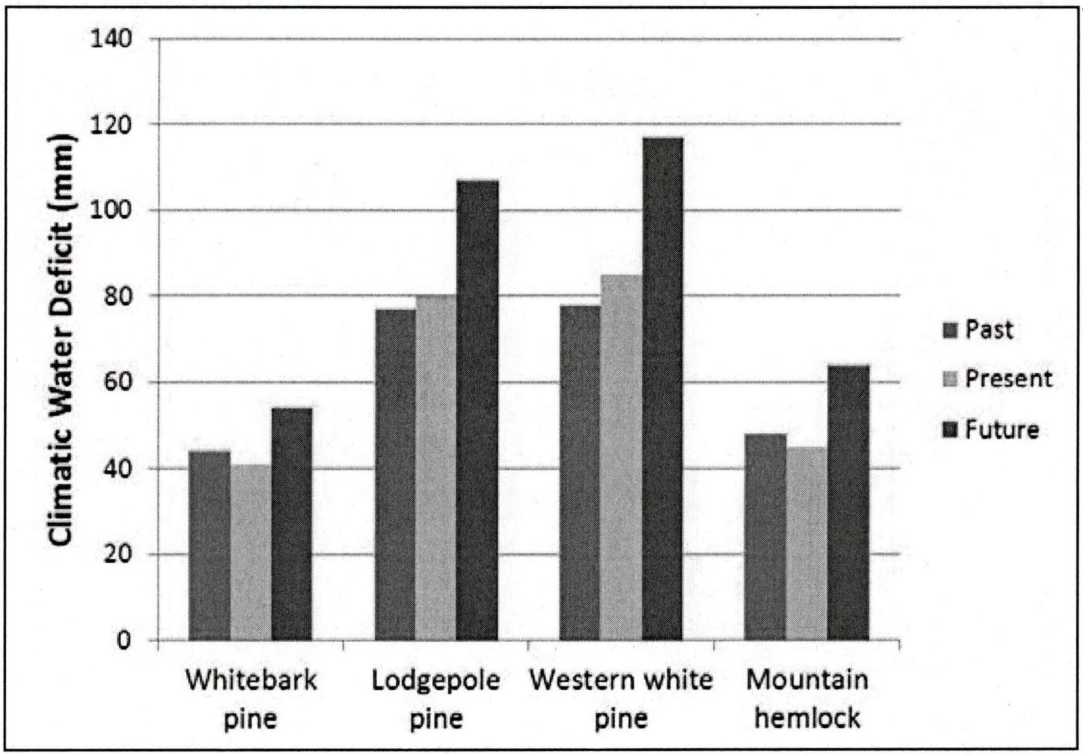
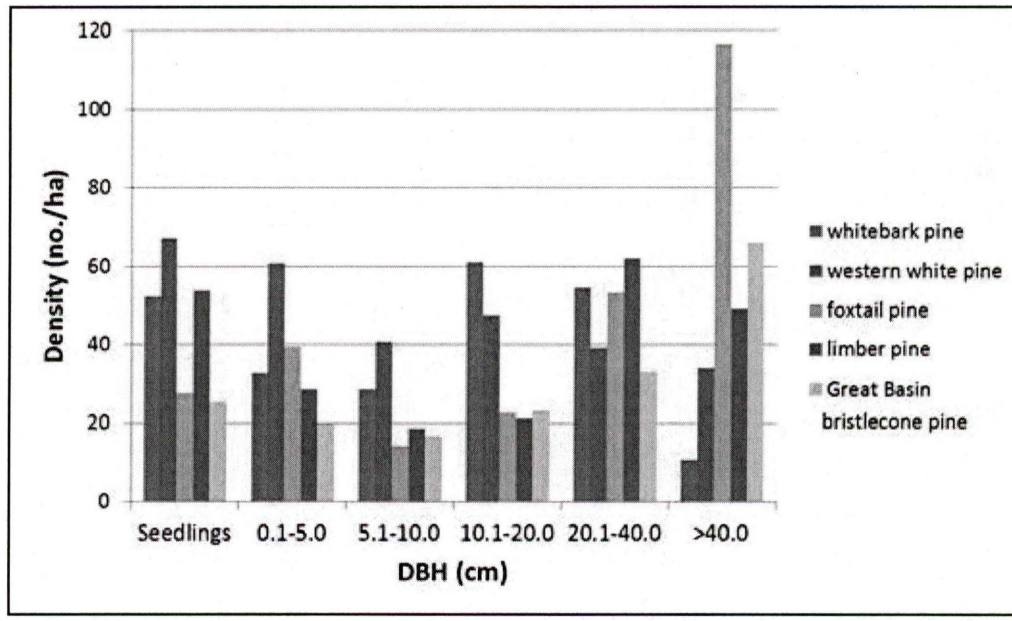


Figure 9 – Tree size class distributions of subalpine stands in the assessment area. Top figure is based on high-elevation white pine forests from Maloney et al. (2008) and Maloney (2011). Bottom figure is based on a total of 301 Forest Inventory and Analysis plots (2012) of subalpine forests (all types) covering the entire assessment area.



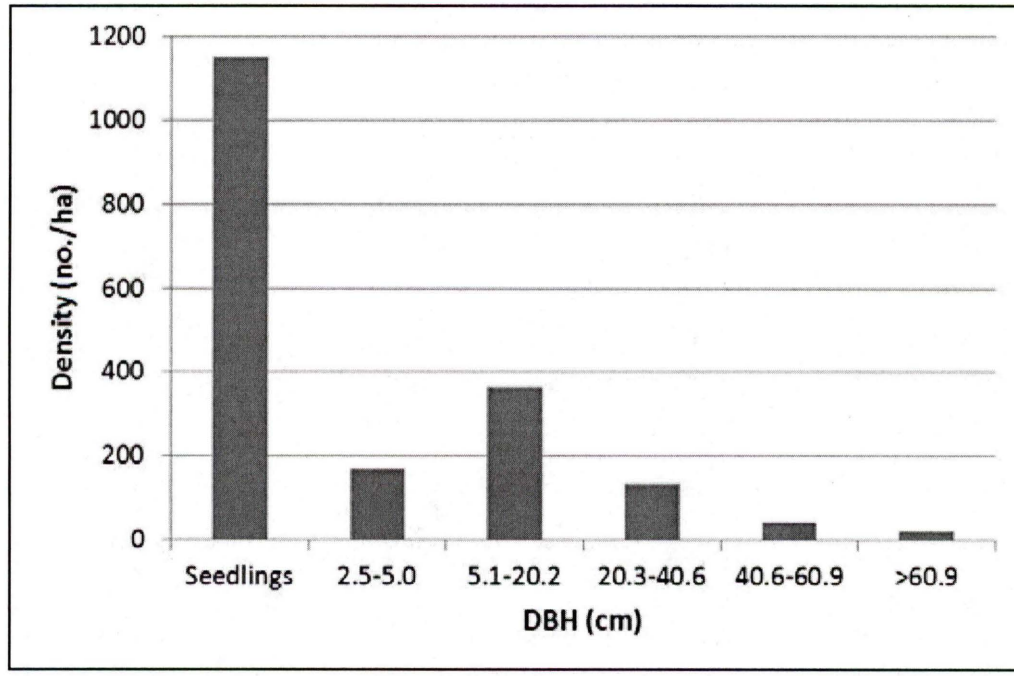


Figure 10 – Mean (± SD) tree density in historic (1930s) and current (2001–2010) subalpine forests (>3000 m elevation) of the central and northern Sierra Nevada. Figure redrawn from Dolanc et al. (in review). Asterisks represent statistically significant differences ($P < 0.05$) between historic and current periods.

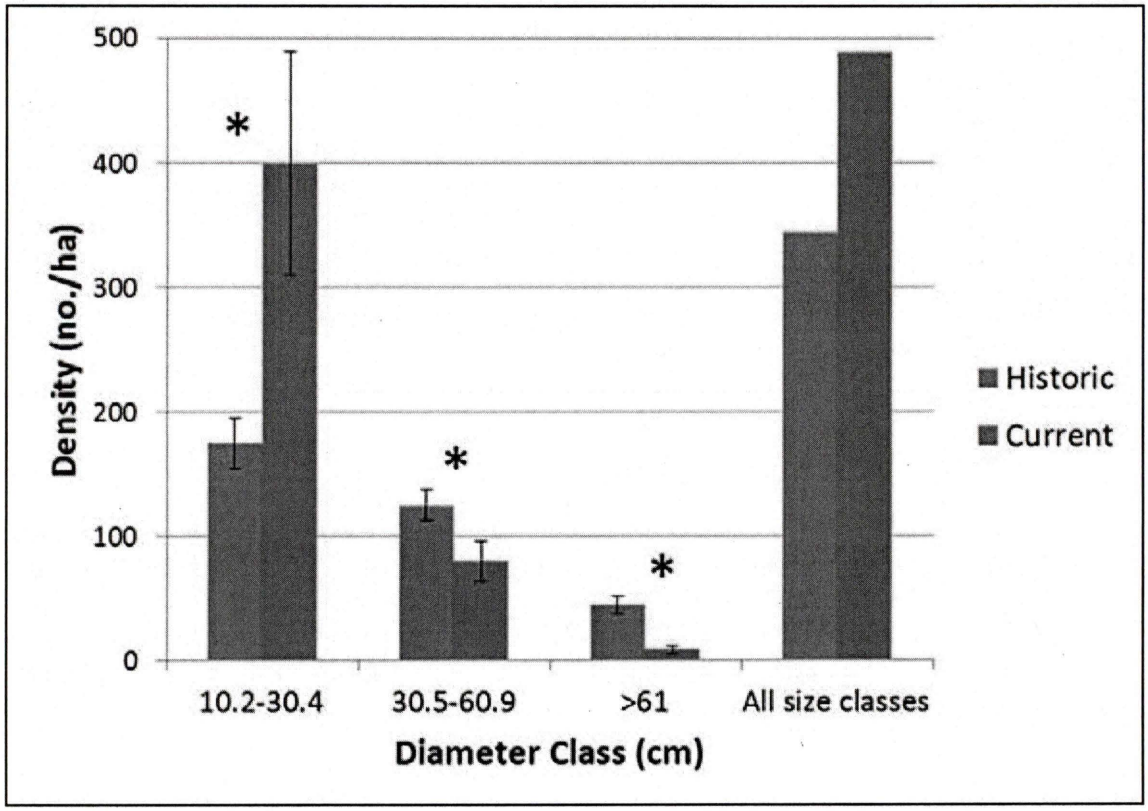
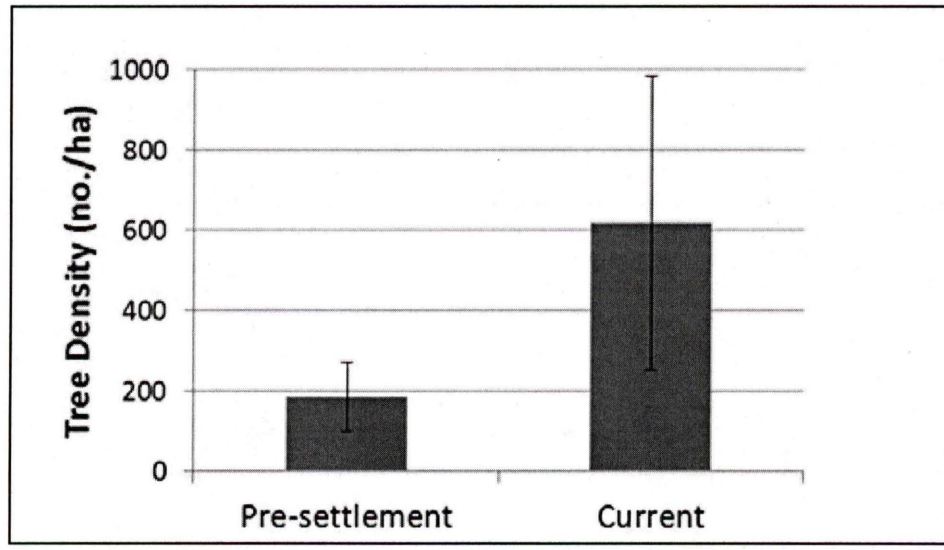


Figure 11 – Mean (± SD) tree density (top graph), basal area (bottom graph), and tree diameter (bottom graph) in pre-settlement (before 1870) and current (~2000) lodgepole pine forests of the Lake Tahoe Basin. Data source is Taylor (2004).



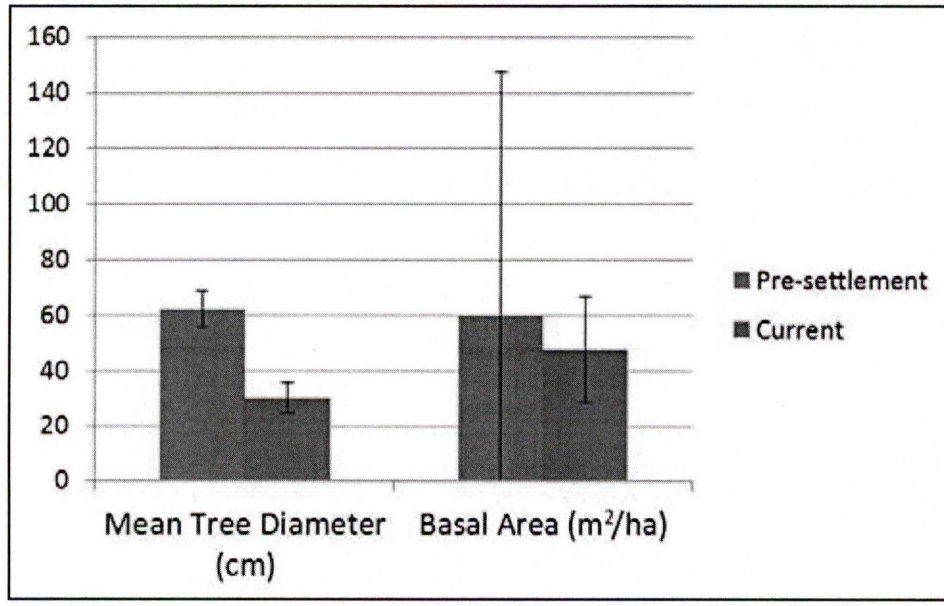
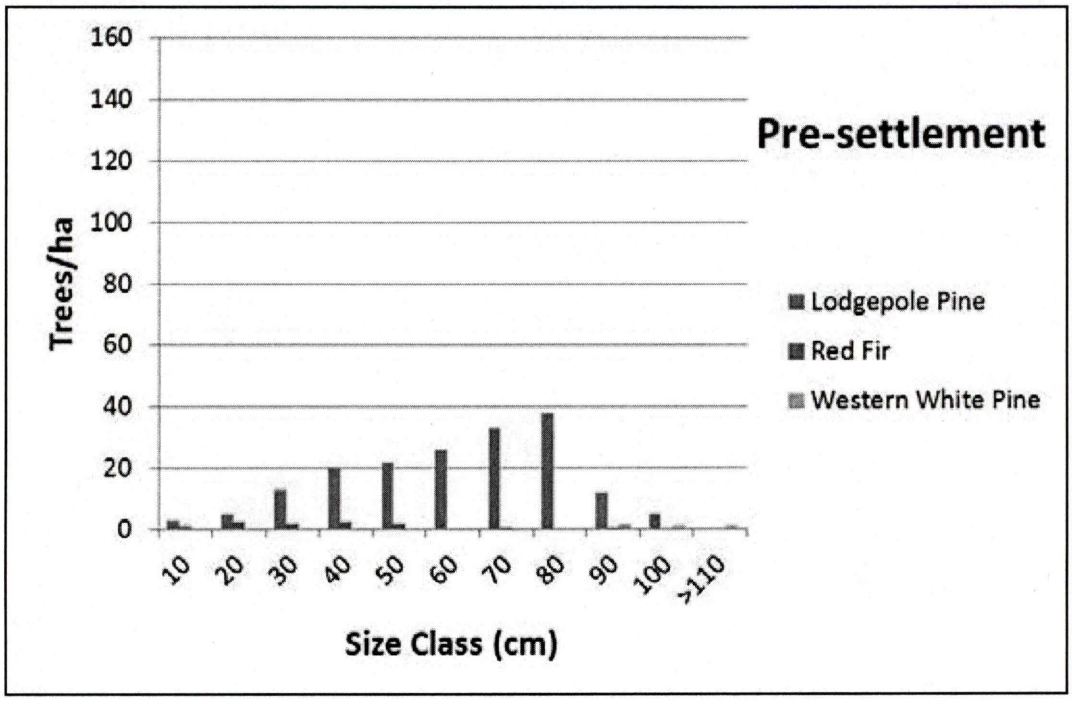


Figure 12 – Tree species composition and size class distribution of presettlement and current lodgepole pine stands that were heavily logged in the late 19th century in the Lake Tahoe Basin. Y-axis scale was fixed at a maximum of 160 trees per ha to emphasize differences in tree densities between periods. Figures redrawn from Taylor (2004).



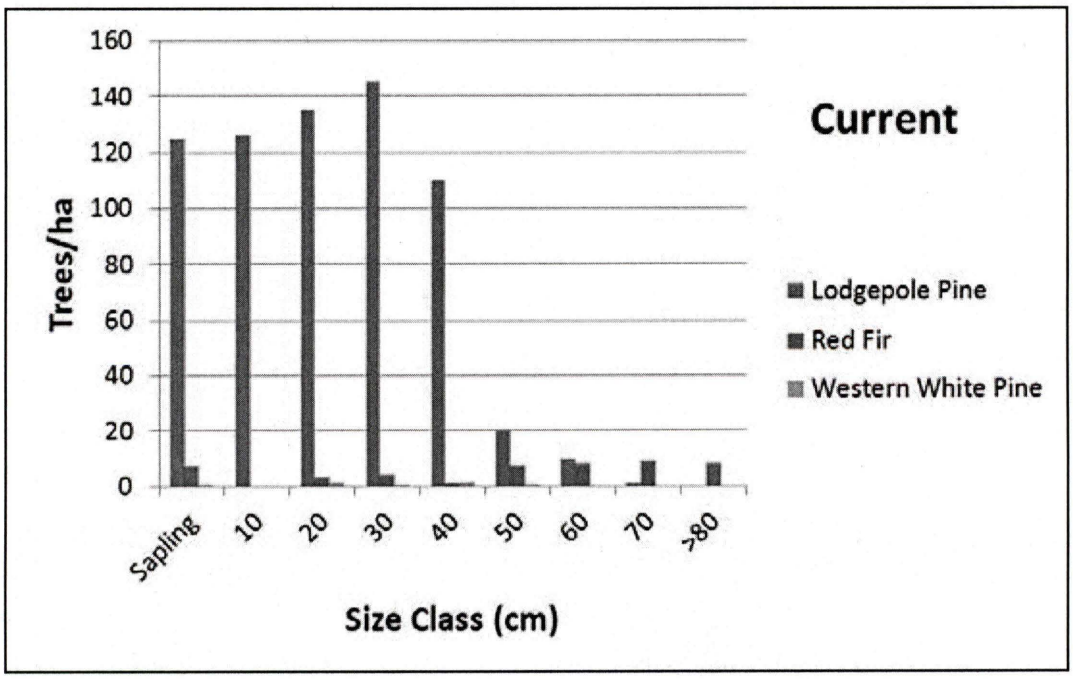
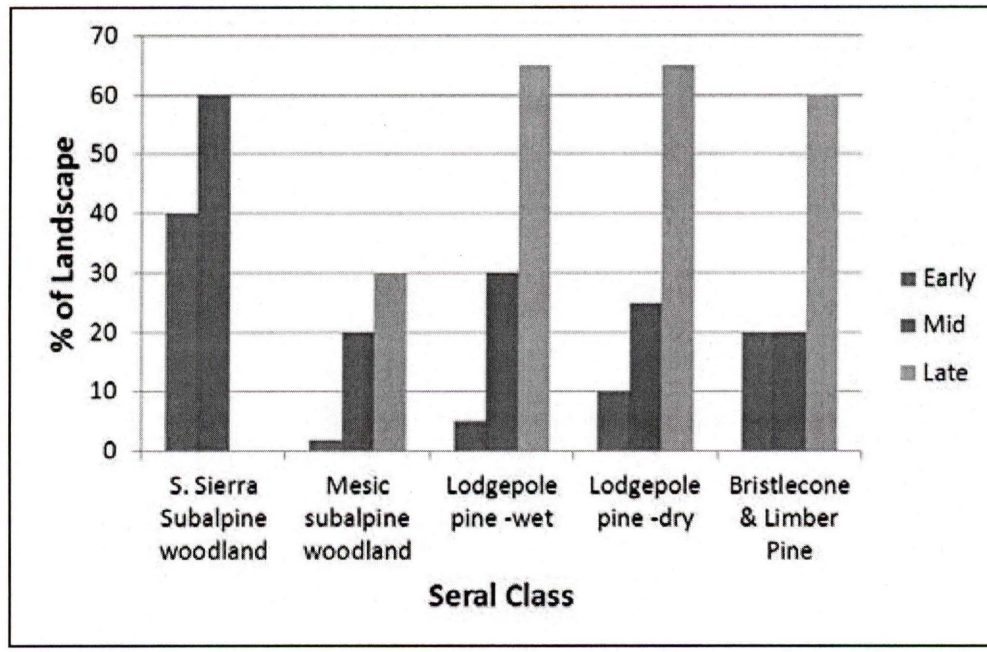


Figure 13 – Percent of subalpine landscape in different seral classes based on LANDFIRE biophysical setting models for the Sierra Nevada. Top figure shows early, mid, and late-seral classes for five subalpine forest types. Bottom figure displays open and closed canopy subclasses in mid- and late-seral classes. Southern Sierra "dry" subalpine woodland is typically dominated by whitebark pine or foxtail pine, but may include western white pine, lodgepole pine, mountain hemlock, and red fir. Mesic subalpine woodland is dominated by mountain hemlock, lodgepole pine, western white pine, and red fir. Data sources are Caprio (2005a, b), Richardson and Howell (2005), Stephenson et al. (2005), and van Wagtendonk et al. (2005).



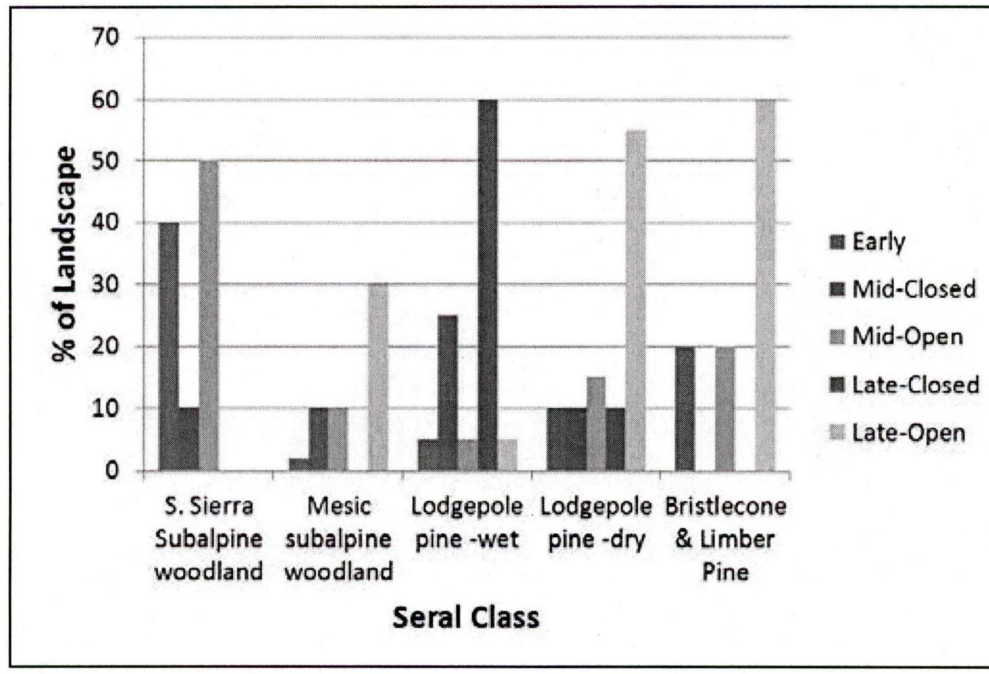
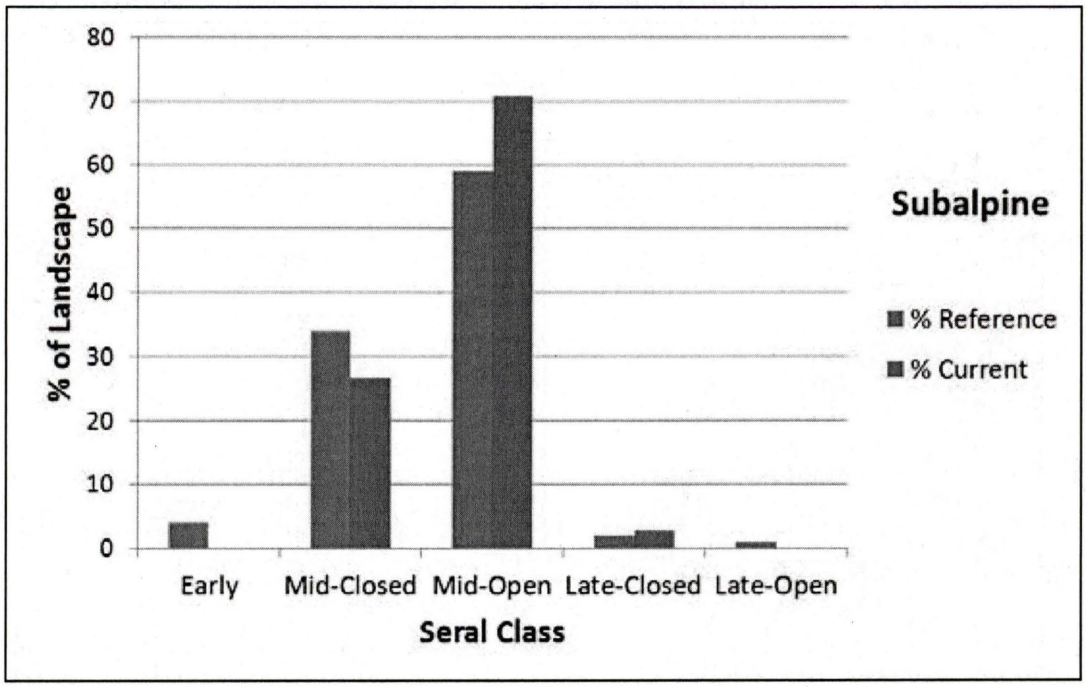


Figure 14 – Percent of reference (i.e., historic) and current subalpine and lodgepole pine–dry forest landscapes in different seral classes based on LANDFIRE Biophysical Setting (BpS) models for the Stanislaus National Forest. Top figure displays the open and closed canopy subclasses within mid- and late-seral classes for subalpine forest (i.e., southern Sierra subalpine forest and mesic subalpine woodland). Bottom figure displays three seral classes for logepole pine–dry forest. Data source is Safford and Schmidt (2006).



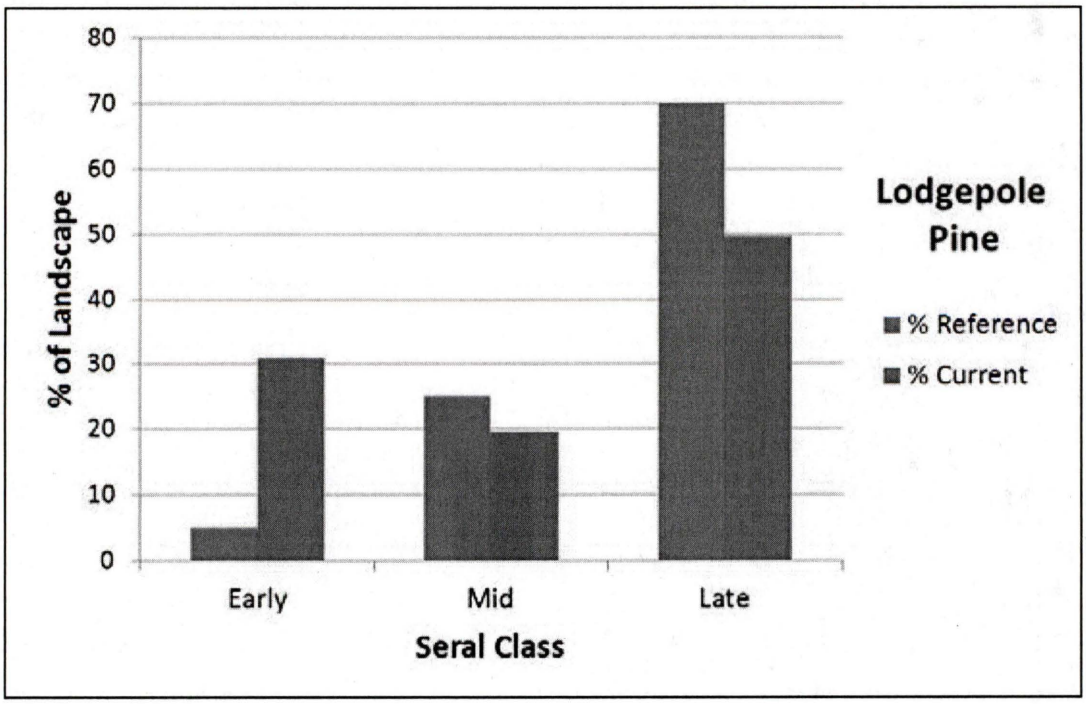
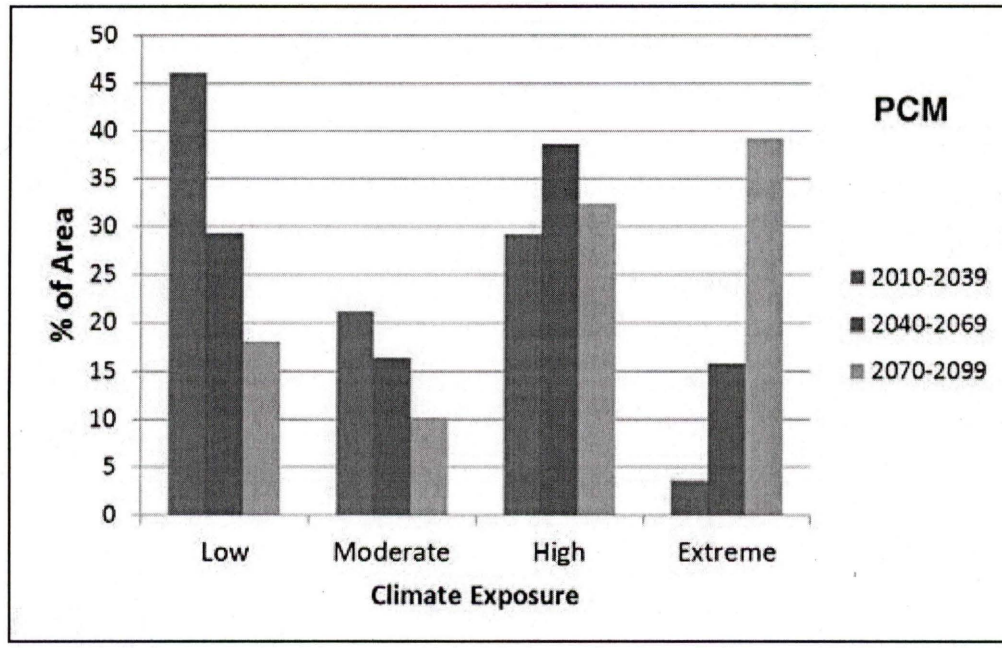


Figure 15 – Future projections of climate exposure for subalpine forest in the southern Sierra Nevada national forests (primarily Sequoia, Sierra, and Inyo National Forests). Projections by Schwartz et al. (2013) are based on the PCM (top graph) and GFDL (lower graph) global climate models, including three future time periods: 2010–2039 (near future), 2040–2069 (mid-century), and 2070–2099 (end of century). Levels of climate exposure indicate subalpine forest bioclimatic areas that are projected to be: (1) inside the 66th percentile (low exposure), (2) in the marginal 67–90th percentile (moderate exposure), (3) in the highly marginal 90–99th percentile (high exposure), or (4) outside the 99th percentile (extreme exposure) of the current regional bioclimatic envelope for subalpine conifers.



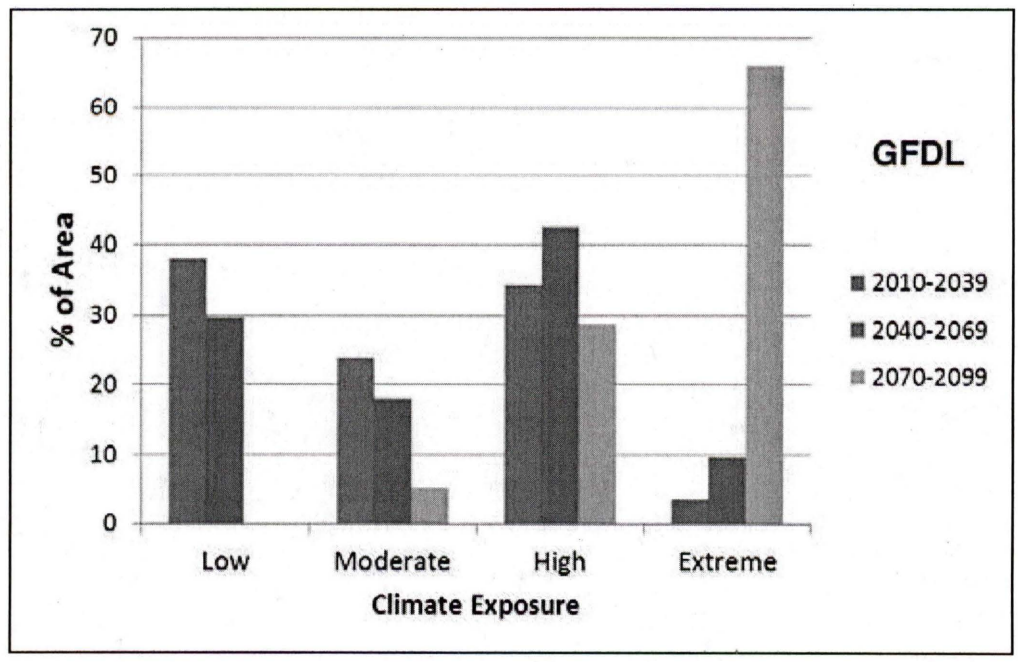


Figure 16 – Future projections (end of century: 2070–2099) of climate exposure for subalpine forests in the southern Sierra Nevada based on the **PCM** model (warmer and similar precipitation). Levels of climate exposure indicate bioclimatic areas that are projected to be: (1) inside the 66th percentile (Dark Green), (2) in the marginal 67–90th percentile (Light Green), (3) in the highly marginal 90–99th percentile (Yellow), or (4) outside the extreme 99th percentile (Red) for the current bioclimatic distribution. Areas in green are suggestive of climate refugia for subalpine conifers by the end of the century. Data source and graphic courtesy of Schwartz et al. (2013).

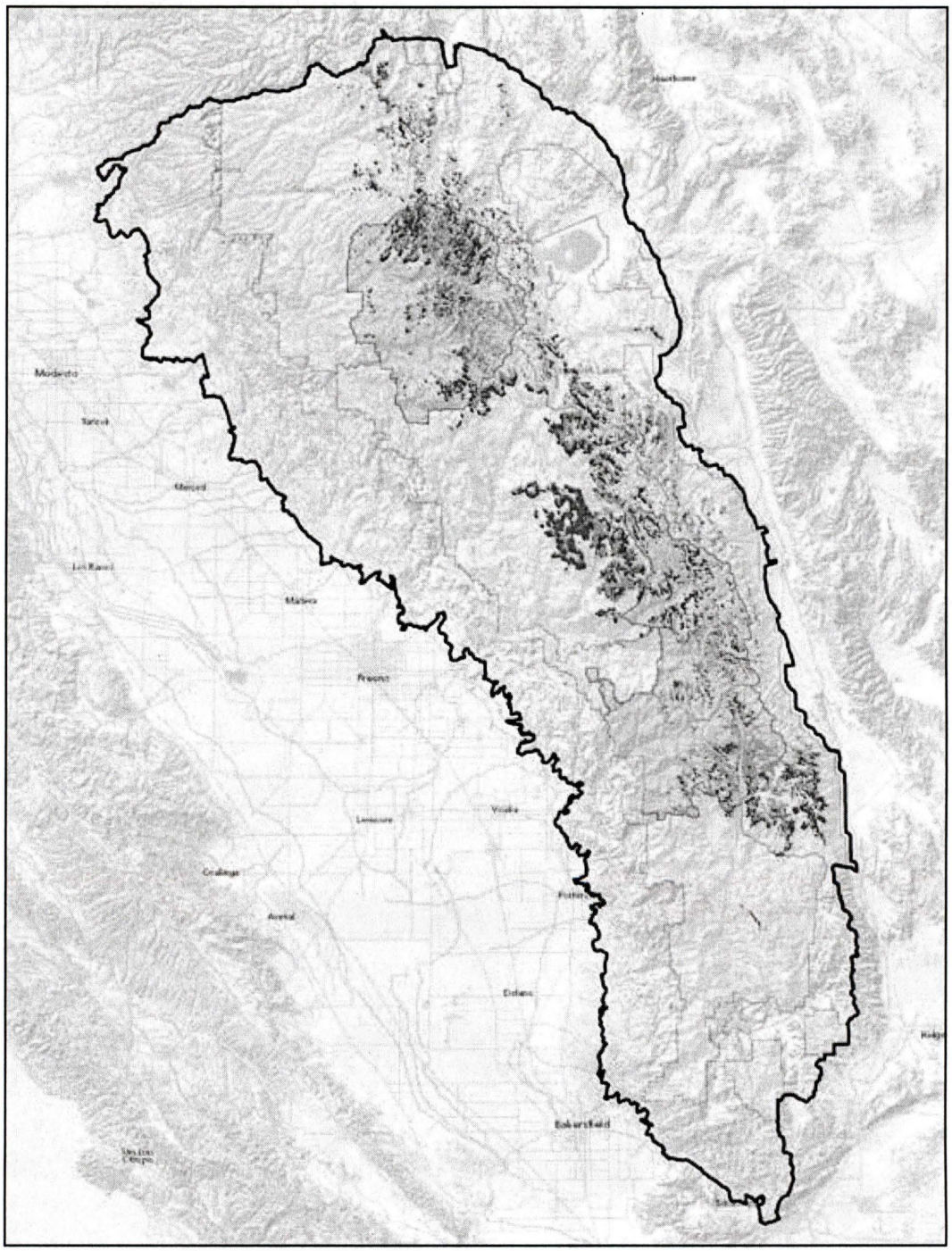


Figure 17 – Future projections (end of century: 2070–2099) of climate exposure for subalpine forest in the southern Sierra Nevada based on the **GFDL** model (hotter and drier) produced by Schwartz et al. (2013). Levels of climate exposure are described in Figure 13. Data source and graphic courtesy of Schwartz et al. (2013).